minneapolis campus
university of minnesota

II: preliminary design information for underground space

august, 1975

prepared by:
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foreword

This report forms the second phase of the development of underground space at the University of Minnesota. The first report provides general information on underground space and base data necessary for physical planning. The specific objectives of the present report are:

1. To complete the general information required for physical planning of underground space.
2. To develop design information for feasibility studies.
3. To develop cost information for feasibility studies.
4. To present recommendations for long-range campus planning of underground space.

The third phase will involve the detailed development which is required for the construction of actual projects. Some of the detailed research and development on the structure of mined space will take place as part of the experimental test room project on campus funded by the RANN program. Energy conservation research on the new underground bookstore/admissions building is also being funded by RANN.

This report was prepared for use by the Physical Planning Office of the University of Minnesota and is not intended to be a comprehensive manual for the detailed design of underground projects. Together with the first report, however, it should provide enough data for underground space to be included as a real alternative in the planning process.

contents

acknowledgements

We would like to thank the staff members of the following departments for their assistance in the preparation of this report:

The Physical Planning Office
The Engineering and Construction Office
The Department of Civil and Mineral Engineering

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1 summary and recommendations

recommendations

- Determine in detail the most suitable locations of portal access to mined space. A small engineering study of each possible location could be carried out by the Engineering and Construction Office of the University.

- Allow for service, construction and possibly parking access to these portals in any long-range plan.

- Consult with the City of Minneapolis, City of St. Paul, Park Board, Corps of Engineers, etc. for any future projects that would affect mined space, i.e. raising the river level downstream of St. Anthony Falls.

- Extend new buildings to bedrock whenever possible. This will maximize the use of available space and also lower costs for adjacent construction because a new retaining wall which is a high cost item would not be required against the existing building.

- When designing new buildings consider underground connections to adjacent buildings and possible integration with mined space.

- Consult with fire officials for possible variances in code requirements for mined space due to the inert nature of the construction. The code requirements govern the number and placement of shafts required which are a significant cost item in mined space.

- Locate major sites for deep cut space to integrate with mined space. A number of possible sites were identified in the first report. The most suitable sites should be selected in the context of the complete planning process.

- Establish major potential transit corridors in cut and cover and mined space. These should be avoided with future construction to facilitate the introduction of a transit system to the University at a later date.

- Consider the location of future utility tunnels and the possibility of grouping them to minimize conflicts with underground space use.

- Document campus hydrology more fully for use in the design of cut and cover space and mined space. This could be accomplished by measuring water levels whenever boreholes are drilled on campus and by installing standpipes from a few sandstone tunnels.

- Compile data on the engineering properties of the geological layers on campus. For instance, when limestone coring is done, the core should be mapped for joints and condition of limestone and a few lengths saved for testing.

- Review the structural and energy conservation information as it becomes available from the research projects in progress on campus.

summary

energy

- Considerable energy savings are possible in underground construction even with high ventilation loads. For low ventilation loads the savings become an even larger percentage of the total energy use for an above ground building.

mined space

- Fifty to sixty foot clear spans should be available in mined space with intervening pillars or ribs of approximately the same dimensions.

- Mined space excavated from the river bluffs can be provided at a comparable construction cost with above ground buildings. The exact relationship depends to a large extent on the future use of the space.

- A tunnel for excavation and service of a unit of mined space should be designed to be easily extended to serve a future unit of mined space more remote from the river bluffs.

- Excavation of two level mined space is more functional and economical than single level for most uses.

- Optimal layout of shafts in mined space is an important locational and cost consideration.

- Simple, flexible systems of space have the maximum potential for future change and growth.

- The location of future shafts in mined space must be considered in relation to the expansion of a space or a change in its use to a function requiring more vertical circulation or mechanical service.

cutand cover space

- Combined excavation and retaining costs per cubic yard of space obtained in cut and cover construction decrease rapidly with increasing areas of excavation.

- Excavating adjacent to an existing basement extending to the limestone has a distinct cost saving due to the reduction in the number of retaining walls required which are expensive compared with actual excavation and removal costs.

- The cost per square foot of deep cut and cover buildings extending through the limestone is comparable with shallow cut buildings because of the reduced temporary retaining costs.

2 architectural considerations

introduction

In this report the section on architectural considerations encompasses a variety of topics from very general aspects of underground space to some quite specific areas. The section is presented in three parts: general concerns, planning and layout of underground space, and design details. It should be noted that the architectural considerations presented here are not by any means intended to represent a complete list of factors in the design process. The emphasis in this section is on the presentation of characteristics and problems unique in underground space. In each part special considerations and preliminary deisgn information are presented with some design alternatives. In addition to providing general information for planning and design, the purpose of this section is to present the design assumptions on which preliminary feasibility studies can be made.

The design of any building is based on the building program and the main characteristics of the spaces within the building. It is also determined by numerous external factors such as special site features, adjacent buildings and spaces, as well as the overall land use and circulation patterns of the master plan for the area. Of course, these design parameters apply to underground space as well as typical surface construction. Some special aspects of underground space design are presented here for two reasons: They take on added importance due to some of the physical limitations of underground space and there are potentially negative psychological effects associated with the underground.

integration with the surface

For any function in underground space there has to be some integration with either pedestrian or vehicular circulation systems on the surface. Some functions such as utilities and other service related uses simply require the most economical and practical access to the surface. However, for functions which require some access by people, a general concern in design is not only the provision of adequate circulation but the feeling of integration with the surface. This is not always possible nor is it always appropriate, depending on the site and the specific use of the space. In mined space, the simplest and most direct integration with the surface is along the river bluffs. A clear transition from the surface is considerably more difficult to achieve in isolated mined space. Some integration with the surface can be achieved in mined space connected to deep cut and cover space.

In cut and cover space, the overall relationship to the surface is obviously less of a problem. Some cut and cover space is simply a part of typical above ground development and presents no special problem in this respect. Integration of totally underground building can be accomplished by the use of exterior or interior court spaces open to the surface level. In addition to providing this orientation to the surface, the use of courts and skylights is the only means of providing natural light underground.

means of entry

A closely related design problem to the integration of underground space with the surface is the entry. Special consideration should be given to the scale and design of the entry since it may be the only visible exterior feature of the space. Entry to the underground through an adjacent surface structure, through an open court, or through a small surface entry pavilion would each produce distinctly different images and feelings about the space.

interior design

Due to the lack of relationship to the outdoors in subsurface space except through courts or unusual sloping site conditions, the interior design of the space becomes more significant. The variety and scale of the spaces are important in order to avoid monotony or a claustrophobic feeling often associated with being underground. The use of larger interior court spaces can provide the necessary variety of space and serve as points of orientation which are important in a windowless environment. Likewise, color schemes can serve to orient people in an organized manner. In any design the general character of the interior spaces is a primary concern, but when there are no exterior views, the use of materials, colors and lighting are extremely important in providing a humane, stimulating environment.

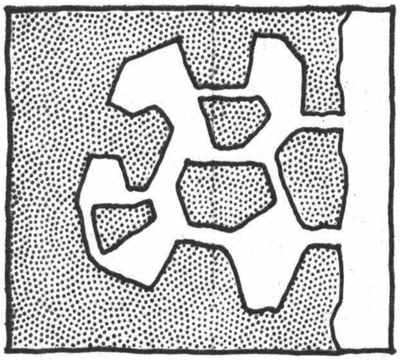
environmental systems

A final point in these general design considerations concerns the basic environmental systems in underground space and how they will function. Almost all of the mechanical and electrical systems will be quite comparable to above ground space since modern surface structures seldom depend on natural light and ventilation. One condition which deserves special attention underground is the acoustical isolation. This lack of noise is an advantage of underground space in eliminating outside noises. However, some background noise is desirable in many spaces to cover minor sounds from adjacent areas. The acoustical behavior of the materials underground may produce some interesting effects and the problem should not be overlooked.

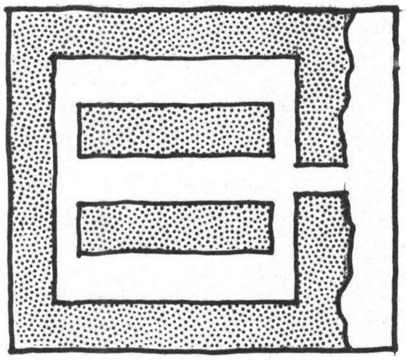
physical limitations

In mined space the bedrock geology and the sub-surface hydrology impose some important restrictions on the layout of the space. At the present time the exact limitations of the limestone roof and the sandstone pillars which support it are not known. However, it can be assumed that spans of 50' to 60' can be achieved with intervening pillars of the same size. In addition to a variety of free form arrangements that can be planned within these restrictions, two basic systems of mining can also be used as an organized structural system: the rib system and the room and pillar system.

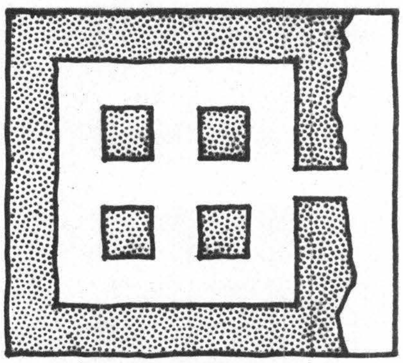
Until more structural data is gathered, the rib system would be a more likely system to use. Then in the future the rib system could be converted to the room and pillar system. It is possible that future developments may indicate that a more efficient system would be 100' spans with 70' pillars, for example. Although this is speculation, it is mentioned so that the present limits of 50' to 60' are not considered absolute.



irregular plan



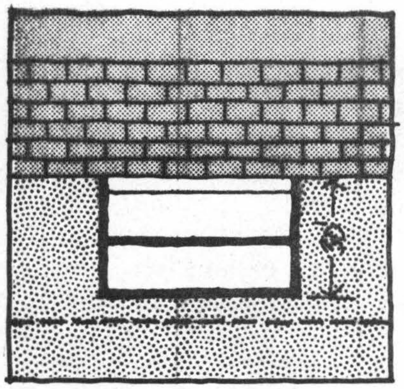
rib system



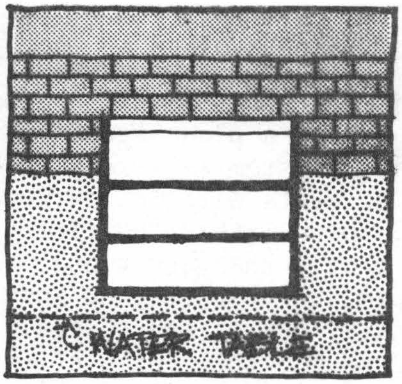
room & pillar system

Another structural limitation that should be recognized is that along the river bluffs where the limestone is exposed and thus in poorer condition, spans may be limited to approximately 30'. This would apply only for the first 50' into the bluff and would basically affect the portal openings. Even at 30' some additional supporting structure may be necessary. Wider openings could be achieved at extra expense with additional supporting structure.

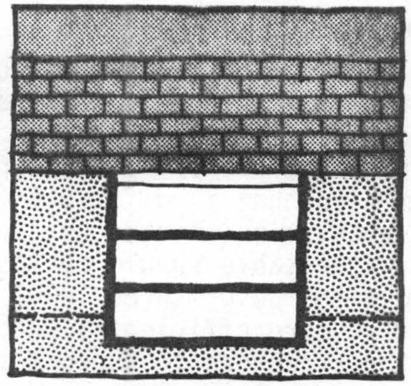
The vertical dimensions of mined space are restricted to an approximately 30' to 40' layer bounded by the limestone layer above and the water table below. These limits can be exceeded but usually at extra expense. The lower layers of the limestone can be removed to provide more space and in some cases, it may be necessary due to the poorer condition of the lowest layer. Generally, this would be a costly operation compared to excavating the sandstone. The lower limits of the space can go below the water table but this, too, would be costly to construct and maintain in a dry condition. The 30'-40' layer allows for two levels of standard construction or possibly three levels of parking. It should be noted that in a rib or room and pillar layout, as the height of the space and thus the pillar increases, the width of the pillar may have to be increased at some point, since its strength decreases with height. This would probably not be necessary at two levels (30') however.



typical mined space



space cut into limestone



space below water table

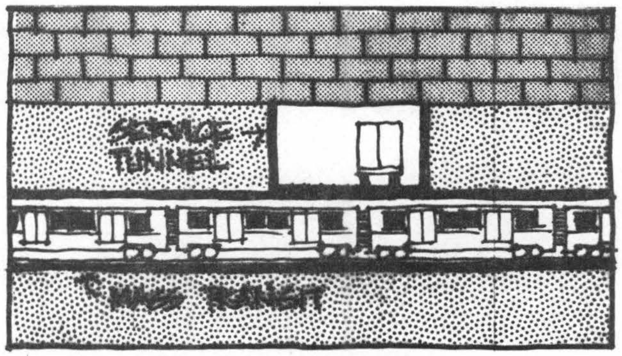
▪ functional implications

Although the physical limitations of mined space are far more rigid than those of surface structures, most major functions can easily be accommodated within them. Only a large auditorium or a large athletic space would require substantially greater spans than 60 feet. Otherwise, the available spans are quite suitable for most office, meeting, laboratory, or recreational functions, and are ideal for parking. Other uses such as storage or maintenance can adapt to this type of layout. In previous studies of mined space for regional transit, the 50'-60' span has been shown to be entirely adequate for large stations.

The maximum vertical dimensions do not put a restriction on any specific space but act to limit the amount of space that can be kept within a short distance. This spreading out is compounded by the presence of the pillars and may make it difficult to house large groups of offices or other spaces that require close proximity to each other. Generally, however, two levels should be sufficient for most immediate groupings of spaces.

Since the vertical dimensions of mined space basically restrict planning to two major levels, the depth of long uninterrupted tunnels for transit or utilities should be carefully considered. Any extensive development of mined space may require access tunnels which would have to cross these service tunnels. Within the 30' of easily available mined space, it should be possible to cross either above or below most tunnels. Presently, large sewer tunnels in the campus area are fairly close to the limestone so the access tunnels could pass below. Some preliminary designs for deep mass transit stations indicate tunnels well below the limestone allowing for crossing above. The coordination of the various levels of these tunnels is an important element in the planning and layout of mined space.

service tunnel below utilities



service tunnel above transit

▪ cost implications

The specific cost estimates of excavation and construction appear elsewhere in the report, but certain basic cost factors with respect to the physical layout can be mentioned here. First, a plan layout that is somewhat regular such as the rib or room and pillar system is likely to cost less than a free form plan that is difficult to excavate with mechanized equipment. Secondly, the excavation of more vertical space within the limits of the limestone and the water table should be less costly than additional horizontal expansion. Also with two or three level space the circulation and service systems can operate more efficiently and costly shafts can be reduced. However, the cost of the structure to support the second level will offset these benefits to some extent.

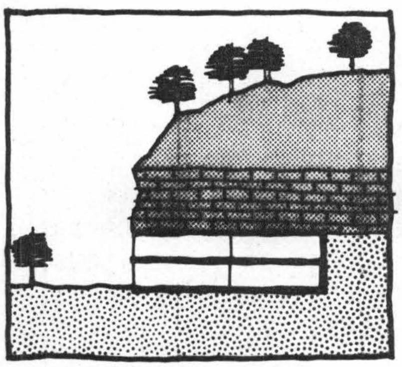
access and circulation

The access to a building by people and vehicles and the related circulation within the building represent basic components of any architectural design. Since most major pedestrian and vehicular circulation occurs on the surface, access and circulation in a surface structure are not usually limited by any great physical restrictions. However, in underground space access and circulation represent a somewhat more difficult problem. In mined space especially, access is limited to a few points and the integration with established circulation on the surface requires careful layout and design. In this section various types of pedestrian and vehicular access are described and some special considerations for circulation are presented.

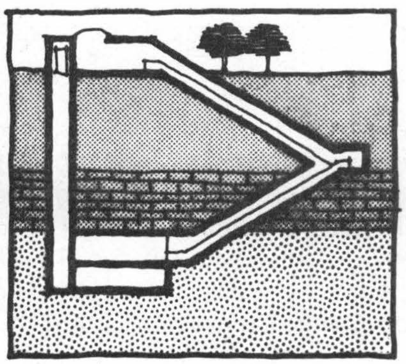
▪ pedestrian access

The types of pedestrian access available in mined space are direct horizontal access from the river bluffs, and access through a vertical shaft containing elevators or a diagonal shaft containing escalators. Although stairs are required for escape, they cannot be considered a basic means of access to space so far beneath the surface.

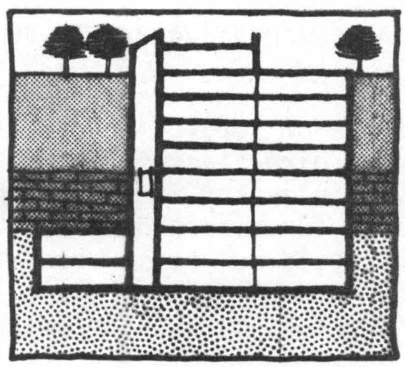
Access is also available from the lower levels of a deep cut building but an elevator or escalator is still the means of conveyance. Some of the variations and combinations of these types of access are illustrated below.



portal access



shaft access



adjacent bldg. access

Each of the first three types of access are different in capacity and, therefore, suitable for different functions. Direct horizontal access from the river bluff has an almost unlimited capacity and ease of circulation which makes it appropriate for any function. Vertical pedestrian access through elevators would be sufficient for most uses but there are some limitations. In any function with large numbers of people entering or leaving at the same time such as auditoriums or transit stations, it would be difficult to provide peak capacity with elevators alone unless a very large bank is provided. For the few functions that do require the movement of large numbers of people, escalators can serve as a major means of access from the surface. The major advantage of escalators is that they provide the continuous flow necessary for moving large groups of people.

Naturally, the elimination of elevator and escalator costs by using direct access along the bluffs, is a definite cost saving. However, this type of access is not always available or the bluff may not represent the most desirable location of the function. In comparing elevators and escalators, elevators offer far more flexibility in the selection of capacity and speed. Thus, for nearly any situation except extremely large capacities, an elevator system will be more economical. One contributing factor to this is that a simple vertical shaft is considerably easier to construct than the much larger excavation and backfill operation required for the diagonal escalator shaft. A final point is that when there is access to mined space through a deep cut building, the circulation systems should be less expensive since special shafts may be eliminated and the elevators or escalators can be used more efficiently since they serve the deep cut building as well.

▪ pedestrian circulation

The circulation system within mined space obviously depends on the function of the space and amount of traffic as it does in any building. Since there are no exterior views or points of orientation except along the river bluff, it is extremely important that the circulation system is simple and easy to understand. Because large pillars must be left for structural support, the horizontal distances are often greater than a comparable surface or cut and cover space. Thus, the horizontal and vertical circulation are limited to a great extent by the code requirements for exits which are discussed in the following section.

▪ vehicular access

Vehicular access to mined space is required for service and parking. The simplest means is again direct horizontal access from the river bluffs. Service can also take place from the surface through an elevator or through the service system of an adjacent deep cut building, since the vehicle does not usually have to actually enter the space. In the case of parking, access to mined space away from the river bluffs becomes more difficult. Two possible means of entering isolated mined space with vehicles are by ramps or mechanical lifts.

In terms of service access, functions can generally be divided into those which require direct access by the service vehicle and those for which access by service elevator is sufficient. Direct access along the bluffs are adequate for any function and service elevators should work for most. The only functions which could not be serviced through an elevator would be storage of large items, maintenance or other physical plant activities requiring direct vehicular access, and theaters or auditoriums requiring large equipment and sets.

For parking, direct access from the bluff seems to be the superior solution. Ramps to deep space would be costly and difficult to construct while mechanical lifts require a great deal of costly equipment, making both solutions economically unfeasible in most cases. However, a large deep cut parking structure may provide workable access to mined space and the ramps to such a depth would be more reasonable since they would be serving many more levels. Of course, the scale of the entire underground development influences the relative cost of these systems somewhat, but access from the bluffs will usually be less expensive and better integrated with the surface roads.

In the case of service, a direct cost comparison of an elevator system from the surface to a service tunnel from the river is not really valid. The determination of the type of service is not based on cost alone but on the actual functional requirements and the site location. In addition, the scale and nature of mined space development influences relative costs a great deal. With the development of any reasonable large area of mined space a service tunnel may extend to areas quite remote from the bluffs.

▪ vehicular circulation

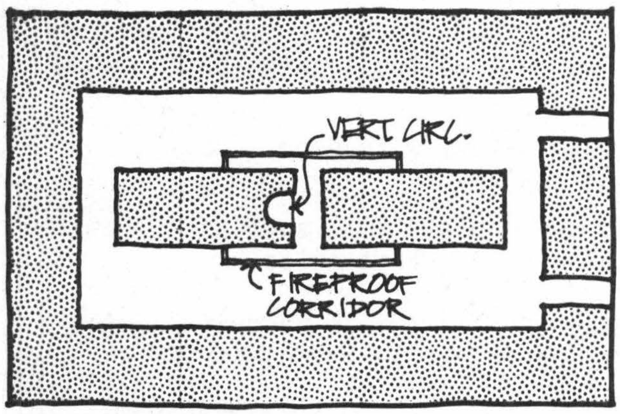
Vehicular circulation in mined space presents no unique problems comparable to those of vehicular access. Parking layouts are demonstrated in the illustrative examples presented in the last section of this report.

code requirements

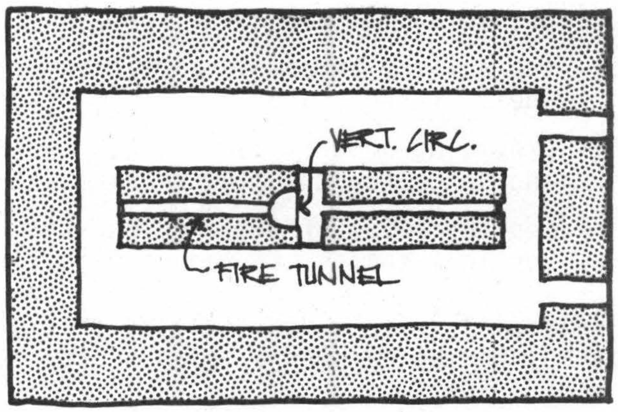
The code requirements which influence the planning and layout of mined space basically relate to the provision of fire exits. In general, for most of the potential functions of mined space, there must be at least two means of exit and no point can be farther than 150' from an exit or 200' if an automatic sprinkling system is installed. These distances do not apply for storage or other low occupancy uses unless hazardous materials are present. Stairs and Escalators must be fully enclosed and smokeproof to be considered as exits. elevators do not usually qualify as fire exits at all. It is possible that for some functions, codes may require fire walls to limit large open areas. This should present no great problem.

In most conventional buildings, the exit requirements do not impose unusual or costly restraints. However, in mined space the relatively high cost of shafts makes optimal placement of exits an important concern.

Due to the unique nature of mined space, with a very high resistance to fire as well as the relatively high costs of providing frequent fire exits, it is possible that variances from the building code may be permitted. If not, there are some methods which may reduce shaft costs by providing horizontal fire tunnels and escape corridors to the nearest shaft.



use of fireproof corridors



use of fire tunnels

In the examples shown here, the area of parking which is within 200' of the fire exit shaft could be extended by the use of fireproof corridors either along the side of the space or within the pillar. A small tunnel in the center of a pillar would not reduce the structural stability of the pillar greatly. However, it would be more costly than a corridor within the open bay. There are many possible layouts where a fire tunnel may satisfy code requirements without additional shaft costs. Another possibility is the provision for an emergency exit into an existing utility or service access tunnel.

flexibility and expansion

▪ flexibility

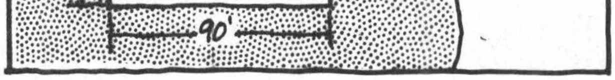
The term flexibility has a variety of meanings and implications. It can refer to the ability to rearrange or subdivide spaces to suit various activities or group sizes. Flexibility can also be achieved by providing a variety of fixed facilities and spaces that are used when appropriate. In such a system the people move to new spaces rather than remain in a changeable space. These types of flexibility can be accomplished in ordinary construction with numerous plan layouts and structural systems depending on the specific program for the building. They can also be accomplished in mined space even with a rather limited variety of structural layouts.

The important difference between mined space and above ground is that once it is created the basic layout can be changed very little. There is no ability to tear it down and replace it with more suitable spaces. Certainly, it can be renovated within the basic structural shell but the shell must remain. For this reason, the long range flexibility of mined space must be considered more carefully than in other types of construction.

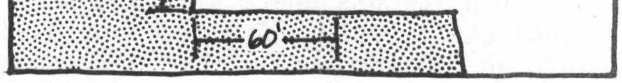
Planning for long range flexibility of mined space leads to certain general considerations in design of the space. These include:

- providing maximum clear spans
- the ability to remove partition walls without destroying the basic shell of the space
- providing orderly service and mechanical systems with good access and space for changing requirements and repair
- concentration of fixed circulation and service systems (such as vertical shafts) to reduce plan limitations and shaft costs

The following example demonstrates that although the immediate program requirements may be met by plan a, plan b provides a more flexible layout for future use.



plan a



plan b

▪ future uses

The determination of what specific requirements should be met in designing a flexible layout is difficult to make, but a reasonable assessment of possible future uses may provide some guidelines. An immediate use such as coal storage in mined space may not require surface access but the plan should reflect logical points of future surface access for likely alternate uses. In another example, a structural bay of 50' may be suitable for storage whereas a 55' or 60' bay would allow for conversion to a more efficient parking layout.

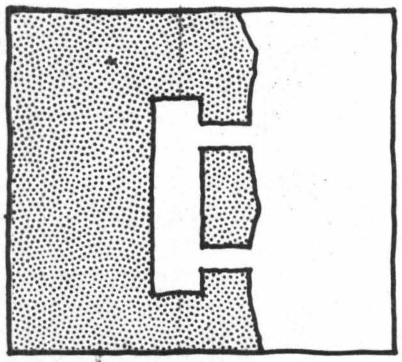
While it is important to strive for an optimal system to accommodate any future use, it is also important to recognize the special requirements of some functions. A mass transit corridor is a unique special use that probably would not be designed as a flexible space.

▪ expansion

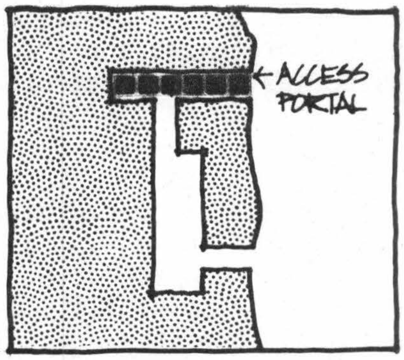
The future expansion of mined space must also be considered an integral part of planning and layout. Any development of mined space will probably occur in phases, and some basic implications of this must be considered.

▪ future access

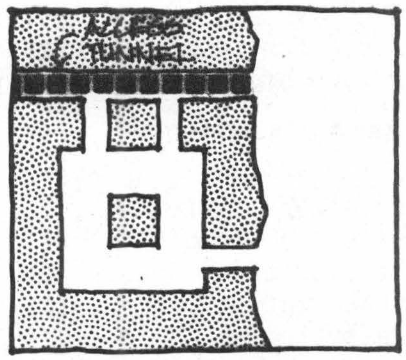
It is likely that first development may occur along the river bluffs where there are points of access for service vehicles as well as construction equipment. Any expansion further into the bluffs will require some type of access for construction if not for service. It is also important to consider the long range possibility of a large scale service loop serving extensive development of mined space. Therefore, portals along the bluff should be points of access to an eventual system of development, not just serving an immediate specific space.



initial development



space with access portal



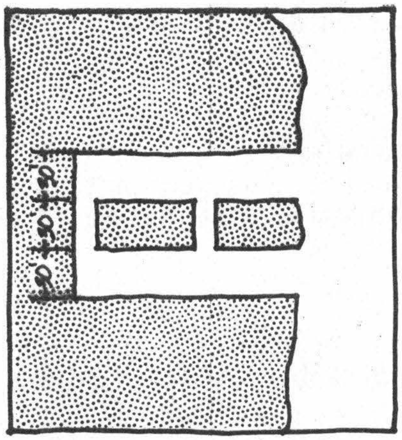
expansion of space

▪ vertical expansion

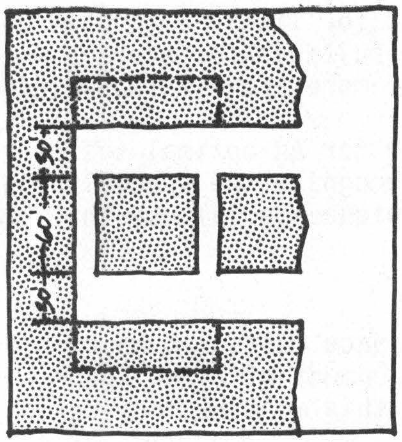
It is possible that expansion could take place by excavating deeper into the sandstone from an existing mined space, although this would most likely result in expensive destruction and reconstruction of the lining of the space. The relative costs of initially providing multi-level space will be presented in a later section on cost estimating.

▪ expansion within structural system

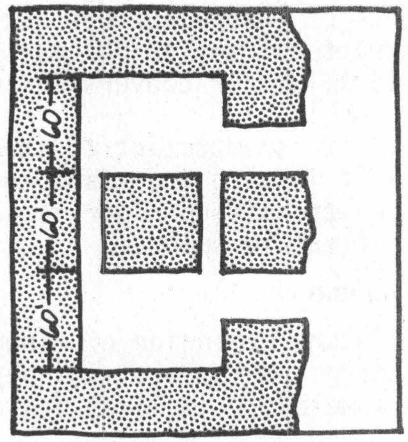
The dimensions and layout of a space are not totally fixed and may be changed within the limits of the structural system used. If a space is planned with future expansion as a consideration, then the dimensions can be changed considerably as long as the intervening pillars or ribs can support the new spans. This is illustrated in the example on the following page. Also in some circunstances a rib system can be expanded to a room and pillar system as previously mentioned.



a- no expansion possible



b- phase one



c- phase two

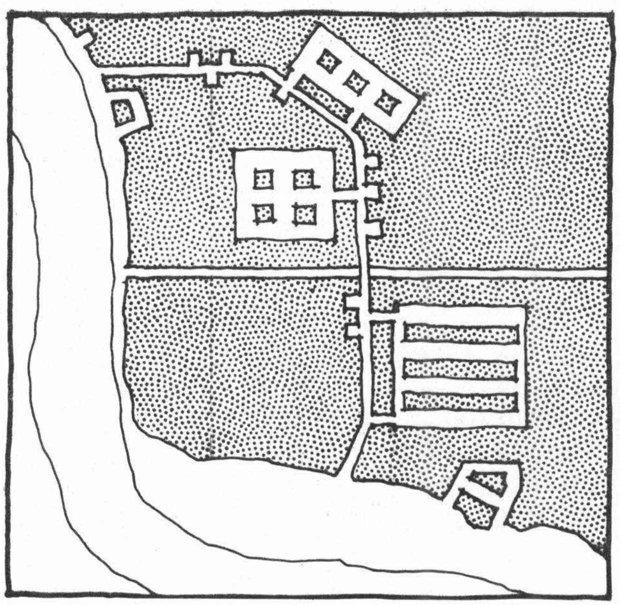
summary

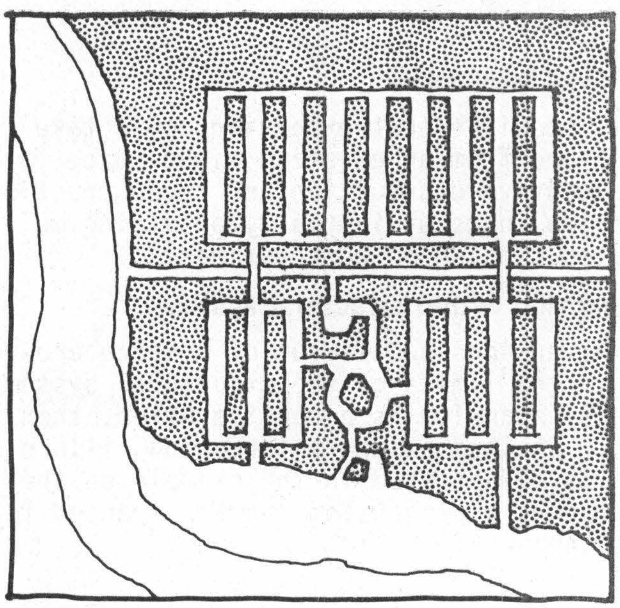
▪ modular plan

The structural capabilities, code requirements, and desire for maximum flexibility all contribute to the planning and layout of mined space. The desire for flexibility and the necessity of expansion in particular, suggest a modular type of system, a system of space which can accommodate a maximum number of possible functions and remain simply organized and intelligible to the user. This type of system is likely to be easier to construct and therefore less costly.

▪ large scale systems

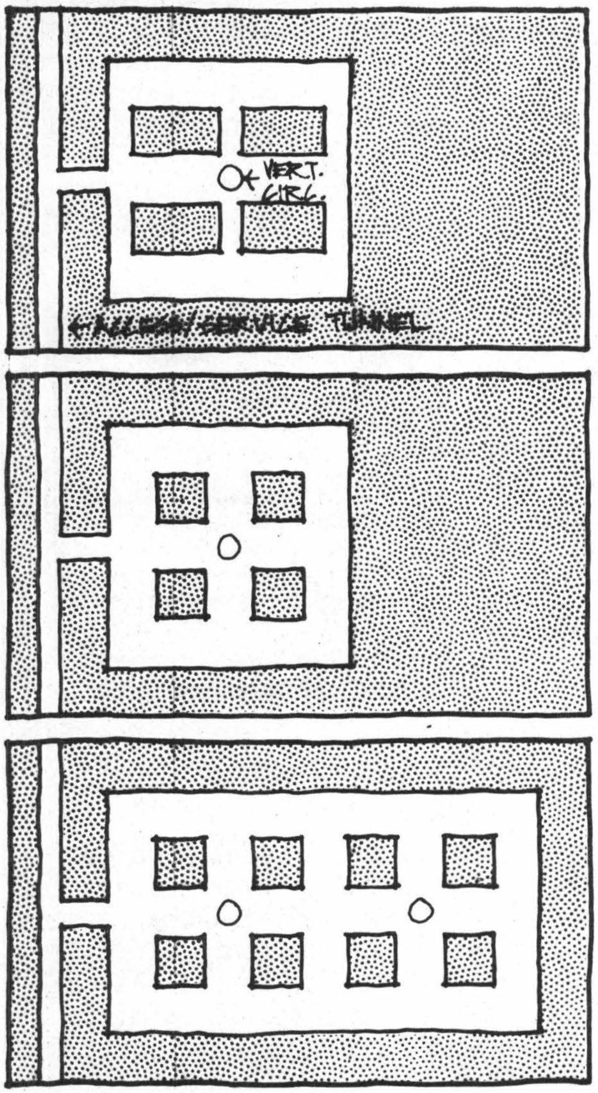
On a larger scale, however, it can not necessarily be implied that the most satisfactory system will be a rigid repetition of a particular structural bay. Perhaps a skeleton of horizontal circulation such as a vehicular service loop may tie together several clusters of mined space development with diverse systems of organization or orientations. Another possibility is a fairly rigid large scale system which includes areas of unique character distinct from the system.



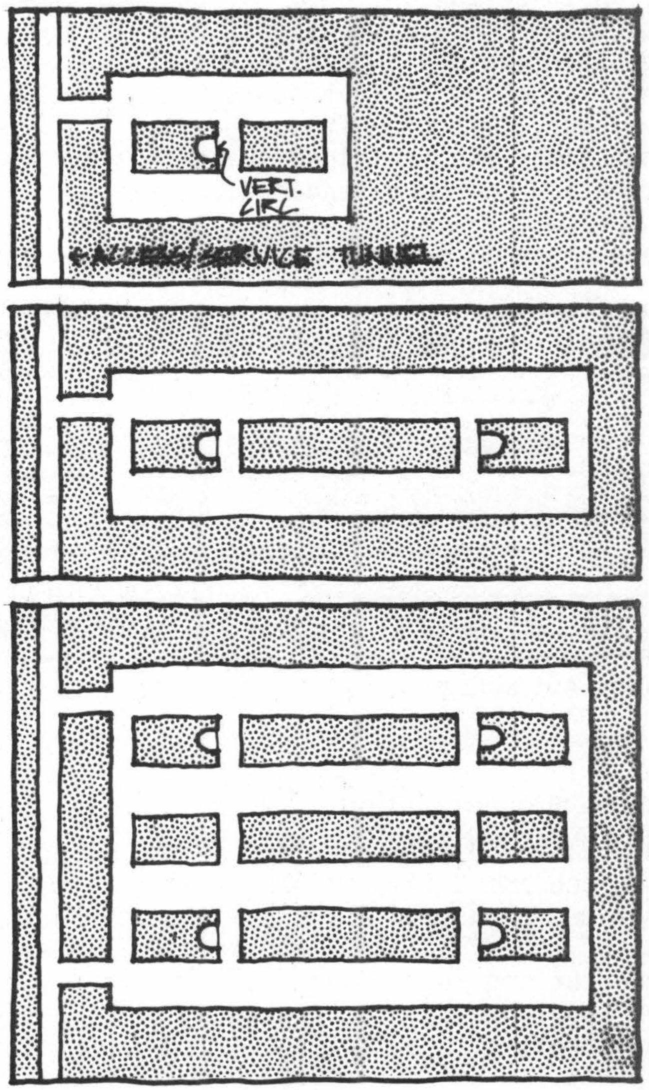


Conclusive research on the structural limitations of mined space in this area has not been completed and potential functions of such space are only speculation at this time. It is possible nevertheless to demonstrate in some examples the basic concepts of modular system of mined space. A basic 50' module is chosen as a span that is expected to be easily achieved and that can accommodate most typical university functions. The systems demonstrated on the following page are the rib system and the room and pillar system.

system a: room and pillar



system b: rib

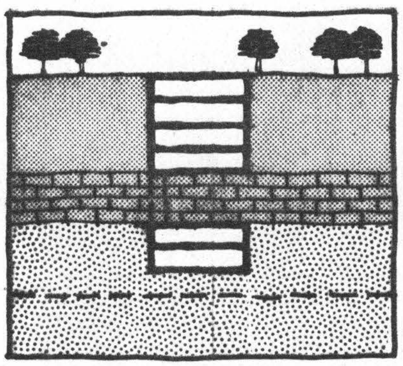


planning and layout of cut and cover space

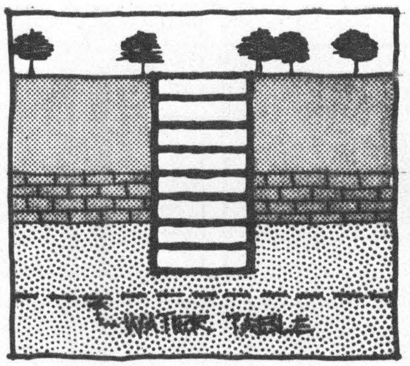
physical limitations

The width of cut and cover openings do not have any dimensional limits imposed by the geology or the nature of its structure. It is limited as any conventional structure is by its site and the available structural systems. Since there are no general physical limitations to cut and cover space, there are no clear restrictions on the types of functions that could occur there.

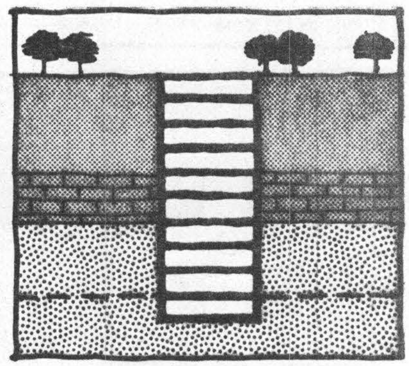
The depth of cut and cover space does present some special considerations and potential limits. The specific costs are discussed elsewhere in the report, but the basic geology should be recognized in planning the lower limits of the space. The first major limitation is the bedrock layer itself which presently represents the lower limit of most cut and cover space. The bedrock can be penetrated and connections made to mined space by shafts through the limestone or the entire excavation can be extended down into the sandstone. The water table about 30'-40' below the limestone layer then becomes the lower economic limit to deep cut space as it is for mined space.



shallow cut space



deep cut space



space below water table

access and circulation

Pedestrian and vehicular access to cut and cover space do not present problems as unique and difficult as those of mined space. Since cut and cover spaces are sometimes a part of a typical above ground development, they simply are an extension of the circulation and service systems of the entire development. In cases where cut and cover space is not part of any surface structures, special attention should be paid to providing clear and simple access and circulation since the overall size and layout of the space is not perceived from the exterior. The proximity of cut and cover space to the surface allows for far better integration with surface circulation systems than mined space does including use of ramps and stairs for pedestrians and ramps for vehicles.

▪ functional implications

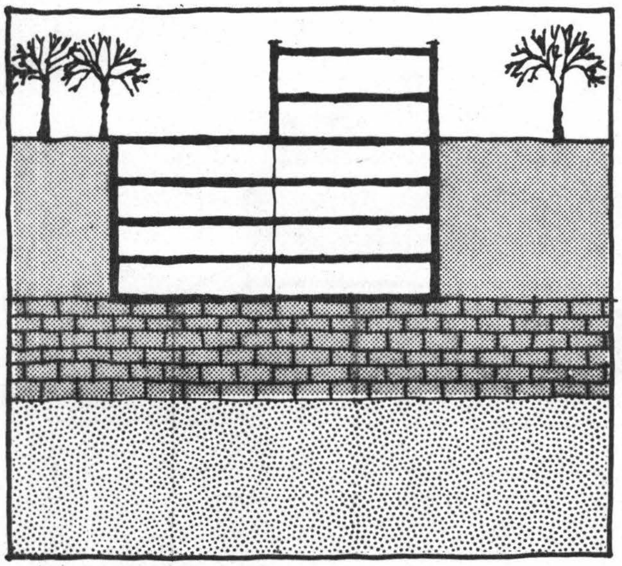
The access and circulation in cut and cover space do not present any limitations to specific functions. However, there are some possible implications on the organization of function. In deeper cut and cover space, the building functions might be organized in the reverse manner of a tall building; that is, with the public and service functions at the top in proximity to the surface and the more private functions with less traffic at the lower levels.

code requirements

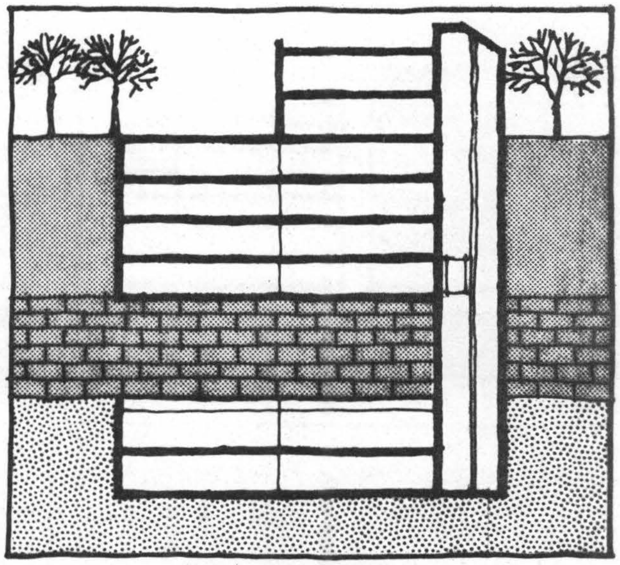
The code requirements which affect the initial planning and layout of space are principally those related to fire exits. The same general requirements for fire exits used for most potential University functions apply to cut and cover space. There must be at least two means of exit and no point can be further than 150' from an exit or 200' if an automatic sprinkling system is installed. In most cases these requirements do not impose any uncommon restrictions on planning cut and cover space unless access to the surface is limited to a few points. In deep cut and cover space which connects to mined space some vertical circulation and means of escape through the deep cut space will most likely serve the mined space as well. In this case, the layout of the cut and cover space will be influenced by the placement of exit shafts to best serve a maximum amount of mined space.

expansion

Typical horizontal expansion should present no uncommon problems in cut and cover space. Since cut and cover space may be adjacent to existing surface structures, there is always the opportunity to connect structures below the surface in order to provide enclosed pedestrian circulation. If this type of connection is a future possibility, this should be a consideration in the initial planning, both to include the future connection in the overall circulation patterns and provide for a relatively simple means of attaching such a connection to avoid unnecessary costs.



initial cut and cover development



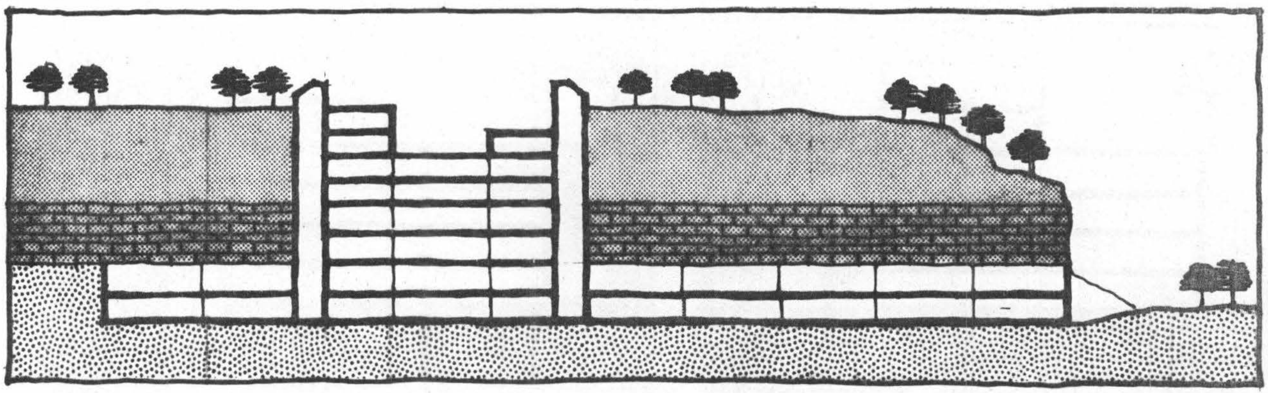
expansion to mined space

Another type of expansion which is somewhat more unique is the connection to mined space. If mined space is considered to be a future possibility, access to the space may be provided from deep cut and cover spaces. This includes both spaces that go to the top of the bedrock as well as those that go into the bedrock. For those spaces cut deep into the bedrock, direct horizontal access to the mined space is an expansion possibility. For spaces on top of the bedrock, vertical shafts through the limestone may provide access to expansion in mined space below. If such expansion is a likely possibility, it becomes an important consideration in the planning and layout of cut and cover space.

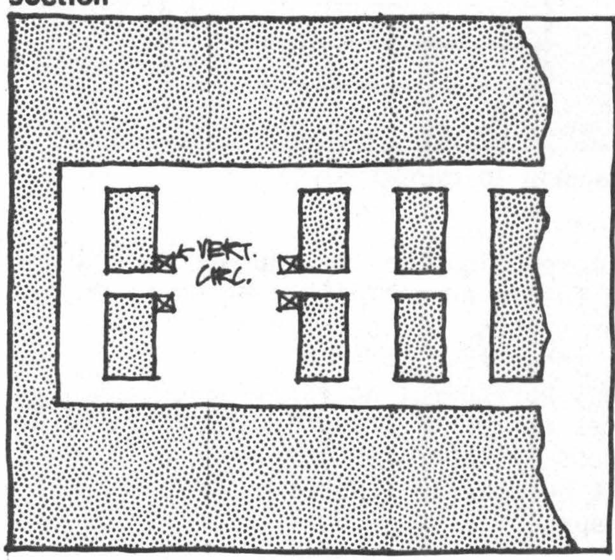
summary

In most general respects the planning and layout of cut and cover space differs very little from that of conventional above ground structures. Certainly there are unique differences such as the means of entry and the orientation of spaces requiring natural light toward courts rather than outward but fundamentally the basic building systems are the same. The physical limitation of space, the access and circulation and the flexibility and expansion of cut and cover space again require some special considerations but do not present completely new systems and problems as are found in mined space. In fact, the special considerations which deserve re-emphasis mainly concern the relationship of deep cut and cover space to mined space.

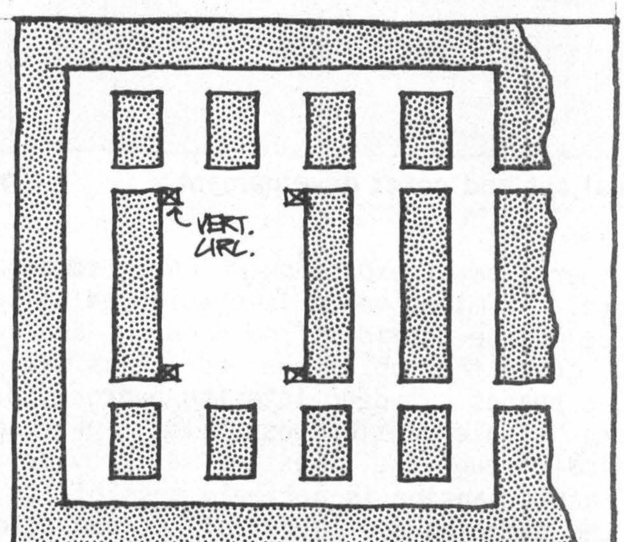
Any potential development of mined space on any reasonable scale requires an orderly system of circulation from the surface. One major means of providing access to mined space is through deep cut and cover space. Therefore, the location and development of both cut and cover space and mined space must be integrated in long range planning. The effect of this on the planning and layout of deep cut and cover space can be demonstrated through the following illustrations. The basic shape, size and distance from the portals contribute to the suitability of this deep basement space as an access to mined space. With this type of arrangement parking or various other functions can be well integrated with the entire building complex. The two plans demonstrate how the layout of the cut and cover space can affect the efficiency of the mined space. In plan b, over twice the area of mined space can be accessible with the same amount of vertical circulation simply because it is located on the periphery, whereas in plan a, any additional expansion would require shafts to the surface.



section



plan a



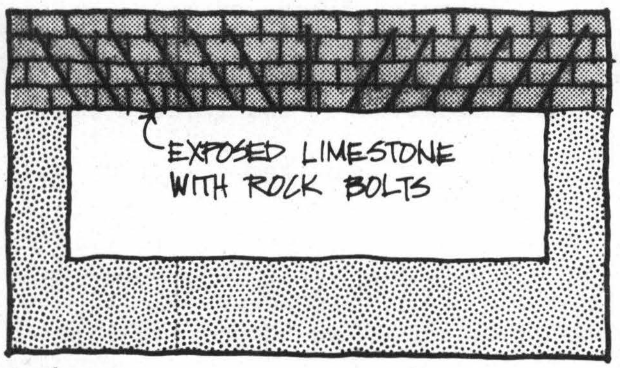
plan b

design details: mined space

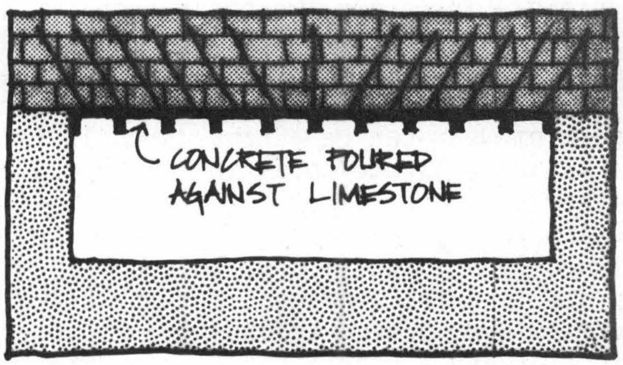
In mined space, it has been determined that in most situations it is desirable to have a maximum open span within some type of modular system. The details shown in this section are illustrated for a 50'-60' bay although they are quite generally applicable. The following details are clearly not the only solutions, but they serve to illustrate the problems and are also used to arrive at preliminary cost estimates.

ceiling systems

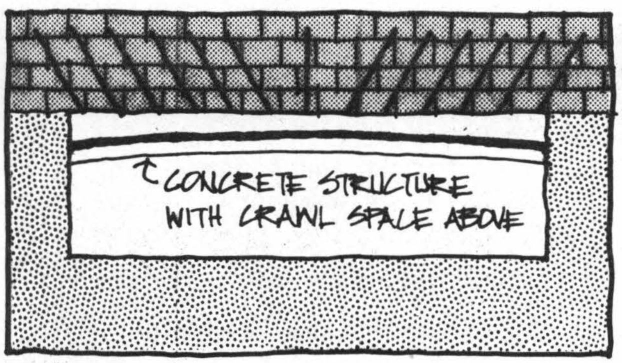
In mined space, the limestone layer acts as a natural structural roof secured by rock bolting. The thin shale layer beneath the limestone acts as an impervious water barrier and creates the perched water table found in the soil. The construction of mined space will require removing the shale and possibly an inferior lower layer of limestone in order to have a sound structural roof. Although the limestone itself is not porous, water inevitably will seep through joints and cracks. Therefore, a basic problem to be faced in mined space is the control and diversion of small quantities of water from above.



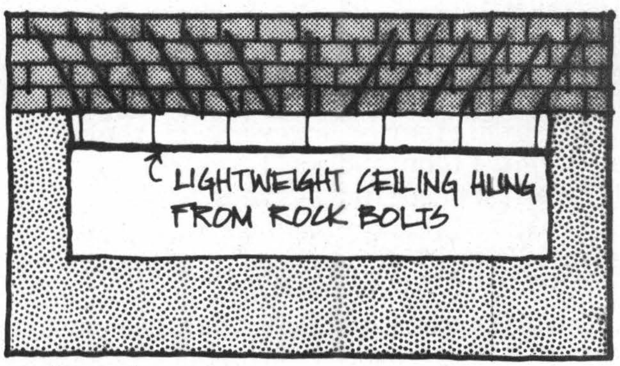
system a



system b



system c



system d

For some functions such as fuel storage or large maintenance areas there may be no need to deal with this problem since a small amount of water leakage may be tolerable. However, for must uses some solution must be found. Sealing joints in the limestone perfectly may be impossible and placing a waterproof membrane against the limestone requires substantial structural support to withstand the water pressure which would develop in time. Another problem related to placing a ceiling tight against the limestone is that it would be impossible to have access to the natural limestone roof to inspect the rock condition and bolts periodically. Therefore, the most desirable location for a second ceiling would be 3'-4' below the limestone allowing a crawl space for inspection.

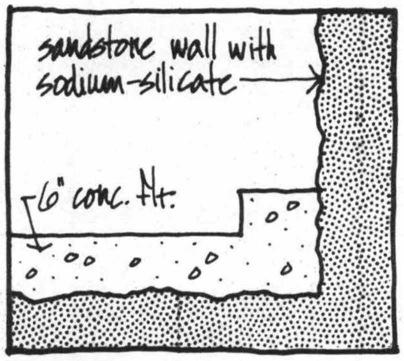
A self-supporting ceiling with a crawl space above it would require substantial structure to span 50' or 60' but would have an uninterrupted waterproof surface on top so that any water seeping through the limestone could be diverted to the edges and down into the sewer system or allowed to drain into the sandstone below the space. The most desirable type of ceiling system for most functions would seem to be a lighter system hung from the rock bolts. A simple water repellant panel such as corrugated fiberglass or galvanized metal would be supported on metal struts and drain to a gutter along the edge of the space. In addition to being lightweight, this system would allow for the removal of panels for any occasional maintenance, such as adding rock bolts without destroying a large ceiling structure.

wall and floor systems

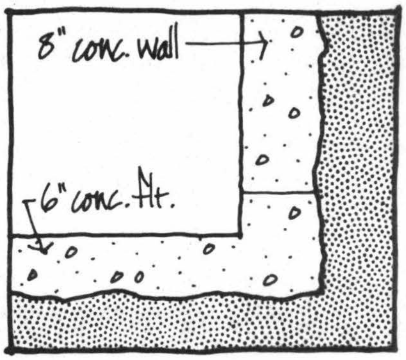
In this area the walls and floors of the mined opening are mainly of St. Peter sandstone. There are two basic problems with the walls and floors of mined space. The first is that the sandstone is somewhat friable or crumbly and exposure may result in wear and even structural failure in extreme cases. The second is the possibility of water seeping into the space. The protection of the friable sandstone from wear can be accomplished in two ways. One is simply the application of a sodium silicate spray which binds a 3"-4" surface layer of the sandstone together and makes it resistant to deterioration and wear. This is an excellent solution for spaces requiring no finished surfaces such as storage. It is likely that nearly any function would require a finished floor, however. The second way of protecting the sandstone is by placing a more durable surface over it. A thin concrete layer poured against the relatively tough sandstone would provide this protection and a smooth surface for the interior space.

If the space is to be designed to withstand total saturation of the surrounding material, any waterproofing on the floor and walls must be structurally capable of withstanding the maximum possible water pressure. In some areas, there should be no problem with water in the sandstone and the exposed wall or concrete lining will be sufficient. However, if there are water problems, the provision of a water tight floor and wall system is not extremely difficult and several high quality waterproofing systems are available commercially. A waterproof membrane requires a relatively smooth surface for application and in mined space would have to be applied from the inside of the space.

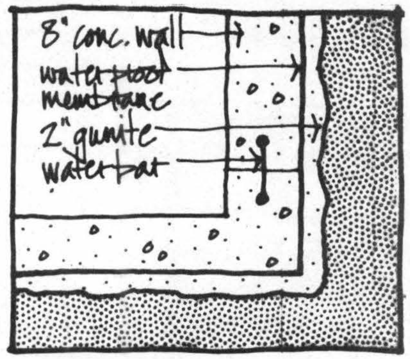
These requirements suggest that one possible solution for the wall and floor system of mined space is a membrane sandwiched between a thin outer layer of gunite applied to the sandstone and a thicker reinforced concrete wall and floor poured inside of the waterproofing layer. If the sandstone could be made relatively smooth, it may be possible that the waterproofing membrane could be applied directly to it without the first layer of concrete. The reinforced wall would be designed to withstand the water pressure. This type of system could be added later to a space if water problems developed in a previously dry area. If there is a possibility of adding a waterproof membrane and reinforced concrete wall later, the space should be designed considering the possible reduction in dimensions.



system a



system b



system c

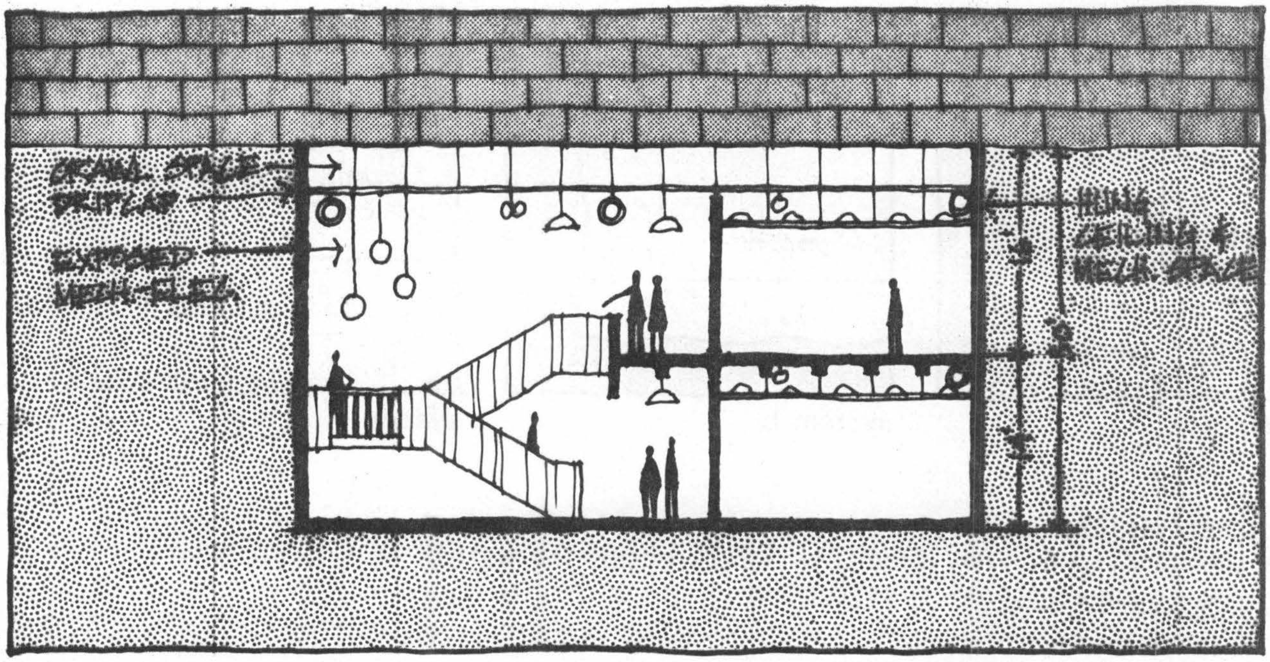
These details are obviously for the exterior lining of mined space in contact with the sandstone. Any floors or walls occurring within this basic shell would be of conventional construction.

utilities and mechanical systems

The location of the various mechanical and electrical systems in mined space are an important consideration both in the general planning and organization of utilities to serve mined space as well as the design of individual spaces.

Presently, numerous tunnels in mined space are used to supply steam and provide sewers for surface structures. The connection of mined space to these systems should be relatively simple and inexpensive compared to surface buildings since no costly shafts are required. However, some pumping may be required to drain into present sewer lines. A more difficult problem with the present utility tunnels is the need to cross or even relocate some tunnels in order to develop mined space. In some cases, utility lines can simply pass through the mined space within the ceiling space or tunnels could even run through pillars. Some existing tunnels may be older and need eventual replacement which could be made to coincide with mined space construction.

The location of the mechanical and electrical systems required inside of a space is not a difficult architectural problem. It is mentioned here to point out some additional considerations and present some illustrative examples of possible arrangements. Using a concrete wall and floor lining and a ceiling system hung from the limestone, a likely place for utilities might be in the space above the ceiling and down through continuous or occasional vertical chases. Systems such as lighting and ventilation would require frequent penetration of the waterproof layer on the ceiling and create possible problems. The crawl space would have to be enlarged to accommodate any additional equipment. Where there is a definite water problem from the limestone, it seems simpler to leave the waterproof hung ceiling intact and locate the systems beneath it. The ducts, conduits and fixtures could be exposed if desired or a second hung ceiling could enclose the mechanical space, both methods being typical construction practice. All of these systems are reasonably flexible and access for expansion or changes in the system should be no problem.



section of mined space

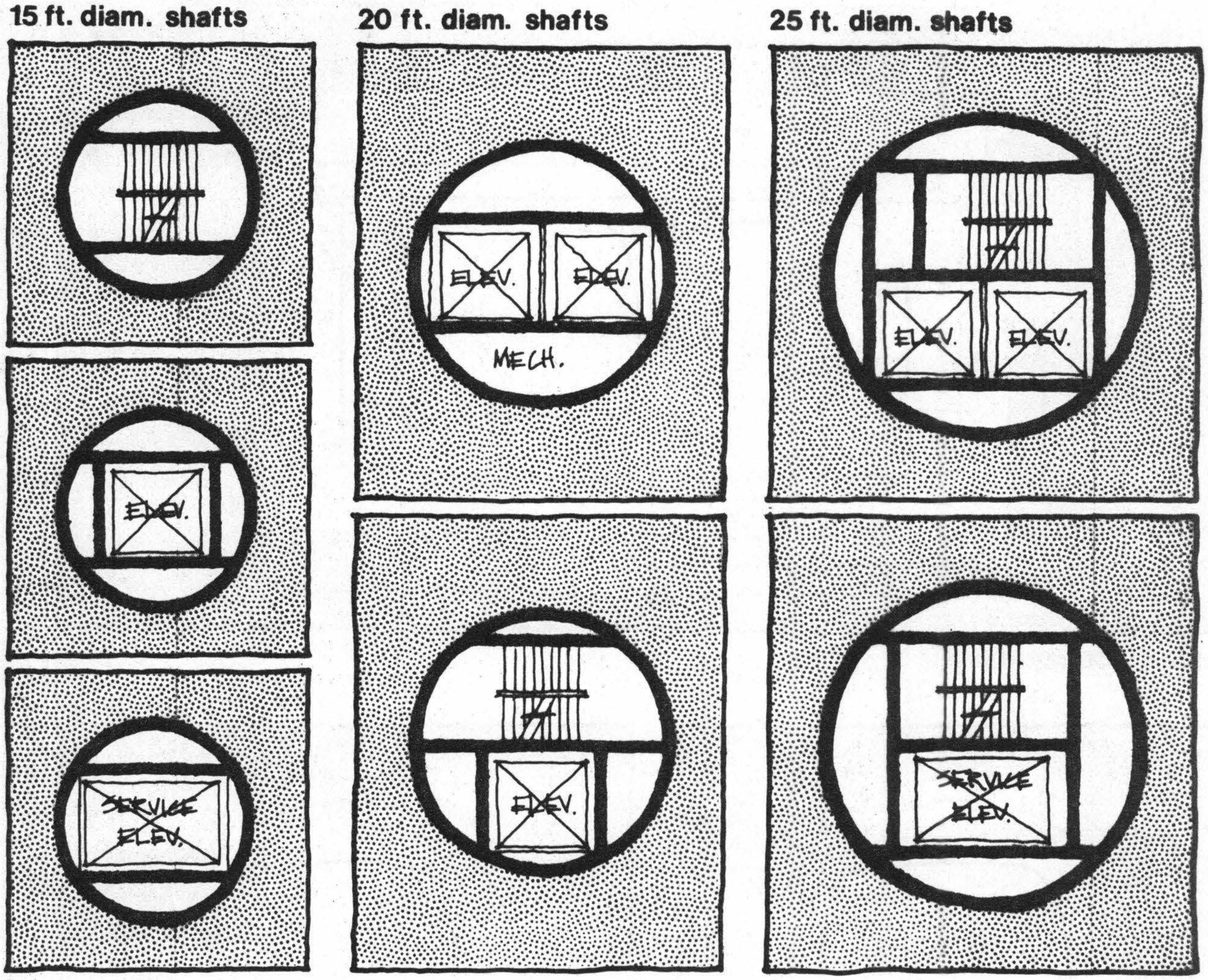
shafts

A basic component of most mined space is the shaft. Shafts are used primarily for access and housing mechanical service to the space below. The types of access include elevators (both passenger and service), fire stairs, and escalators. Elevators for vehicles or spiraling ramps can also be enclosed in shafts to mined space but this is far less likely. The primary mechanical system that occupies substantial space in shafts is ventilation. The size of ducts to the surface depends on the size of the space and the specific ventilation requirements of the function. Another similar use is emergency smoke venting in case of fire. Special vents can open when smoke is present and allow it to escape from the otherwise enclosed space.

In most cases it is easier to construct shafts in a cylindrical shape so the outer wall can act as a compression ring and very little steel reinforcing or interior structural walls are needed. However, in some cases this may not be true. A pair of elevators, for example, may be housed in a rectangular shaft since the wall spans are not large. Most utility shafts in this area are excavated and lined with about one foot of concrete. For shafts enclosing elevators and stairs, it is possible that a waterproof membrane would be included.

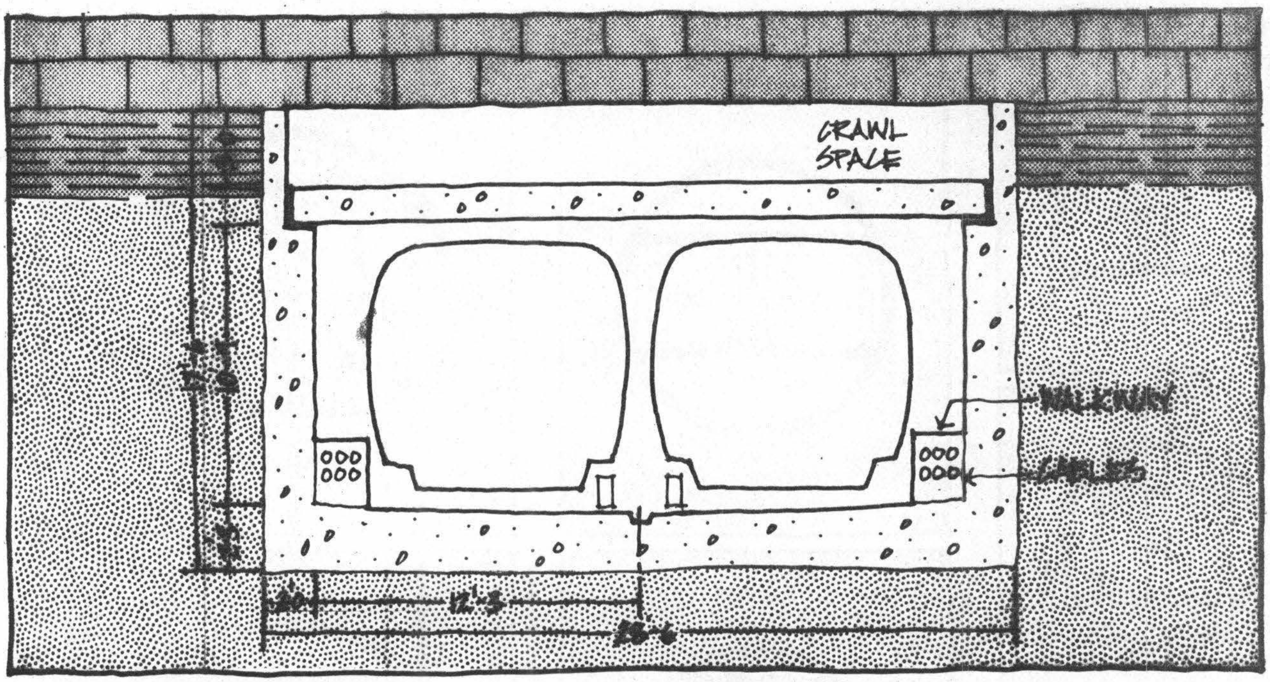
▪ shaft layout

The layout of the shafts in mined space is a critical cost and planning factor. In some cases a number of small shafts with various functions may be appropriate and in others, a concentration of all access and mechanical systems into a few large shafts may be more economical. A few basic shaft sizes and layouts are illustrated here for single and combined uses. These will be used as a basis for determining costs and optimal shaft placement in a later section.

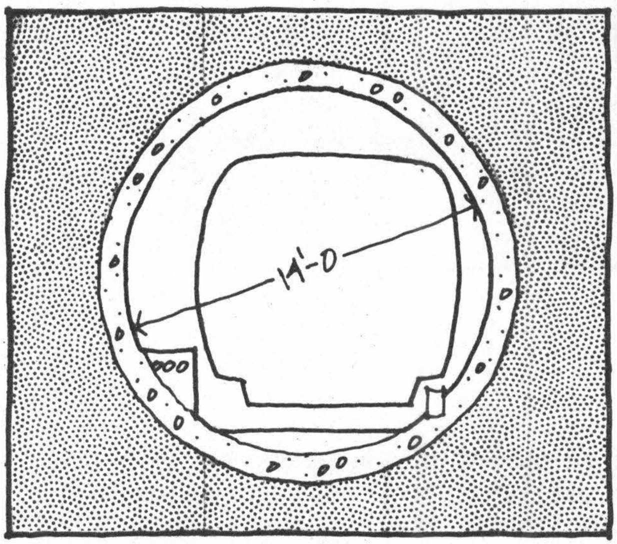


design of tunnels

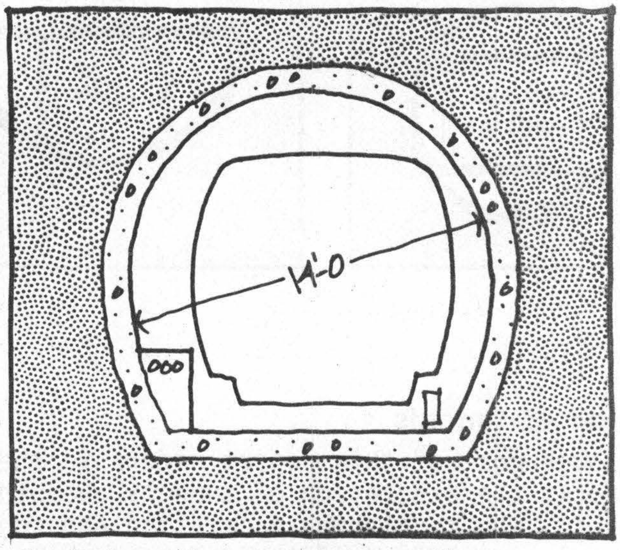
Although most of this report refers to the development of large openings in the bedrock, the excavation of tunnels and other smaller spaces must not be overlooked. The continuing excavation and construction of small utility tunnels is a likely part of any future above or below ground development at the University. In addition to utilities there is the possible development of mass transit requiring somewhat larger tunnels. For general reference and since transit tunnels may have to be coordinated with other mined space development, some typical sections of tunnels are presented here. For typical fixed guideway vehicles, two basic tunnel configurations are possible. The first is a single guideway tunnel of either a circular or horseshoe cross-section. These do not need to be located immediately beneath the limestone. The second is a double guideway tunnel which is similar to typical mined space development located just beneath the limestone. In a relatively unfinished space such as a transit tunnel, waterproofing is not considered necessary and any moisture is collected in a drainage channel. The double guideway tunnel is similar to a typical tunnel for service vehicles to mined space.



double guideway tunnel



single tunnel – circular section



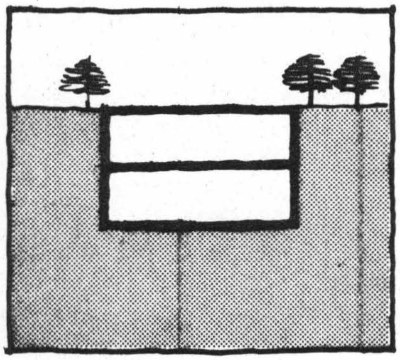
single tunnel – horseshoe section

design details: cut and cover space

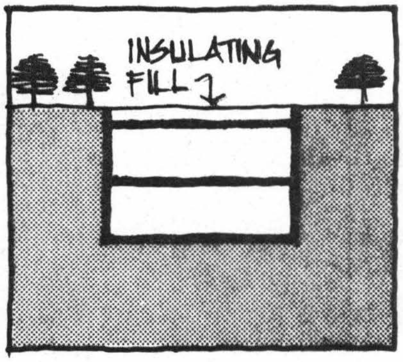
In the case of cut and cover space in particular, almost all of the building systems and construction details are quite conventional and, therefore, will not be discussed here. There are, however, a few basic aspects of detailed design concerning the roof cover, which deserves special consideration. This will be discussed briefly here simply to illustrate the problem and some general solutions.

roof covering

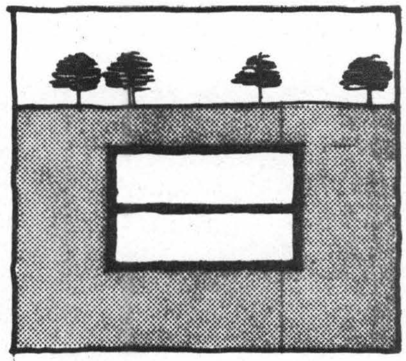
The term cut and cover construction as used in this report is rather general and includes the below grade portion of surface buildings, as well as totally underground spaces to various depths with a variety of roof coverings. In the totally or nearly totally underground structures, the roof is the only surface of the building which is exposed to the surface and has some unique problems and possibilities. One of the primary advantages of underground space is its ability to conserve energy by reducing heat loss and providing a high thermal mass for retention of heating and cooling. In cut and cover space this is provided by the floor and walls but not always by the roof. Of course, a conventional building roof or a deck over underground space can be extremely well insulated by a variety of materials. One product often used on decks or plazas is a poured lightweight insulating fill. Another is a thin layer of polystyrene insulation. One advantage of products such as these is the relatively high insulation value provided without much extra load on the structure. The unique advantage of providing a few feet of earth rather than a few inches of insulation is not so much in superior insulating value based on the transmission, but the great thermal capacity of a larger mass which has the ability to retain heating or cooling over longer periods in the daily cycle and result in substantial energy savings. Nevertheless, the alternative of using earth to cover the structure requires substantially more structural support and it is doubtful that more than a thin layer of earth is economically justified. There are other considerations in the design of the roof covering such as aesthetics which cannot be evaluated in general.



section a



section b



section c

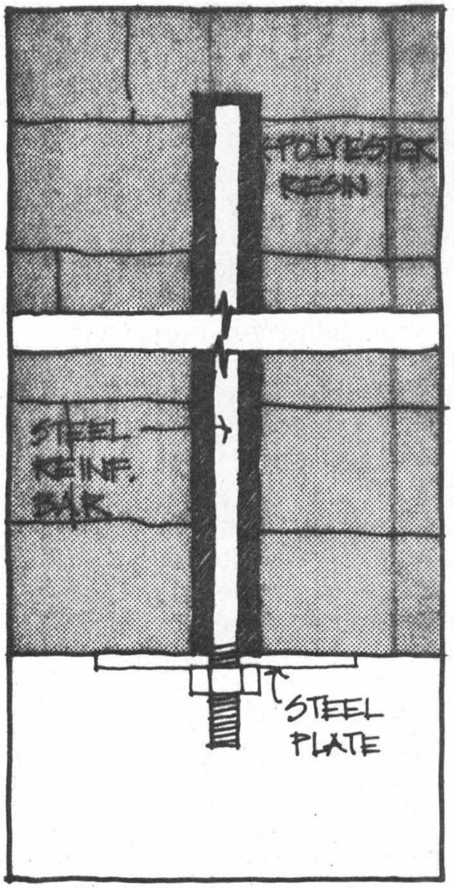
3 structural and construction considerations

roof design

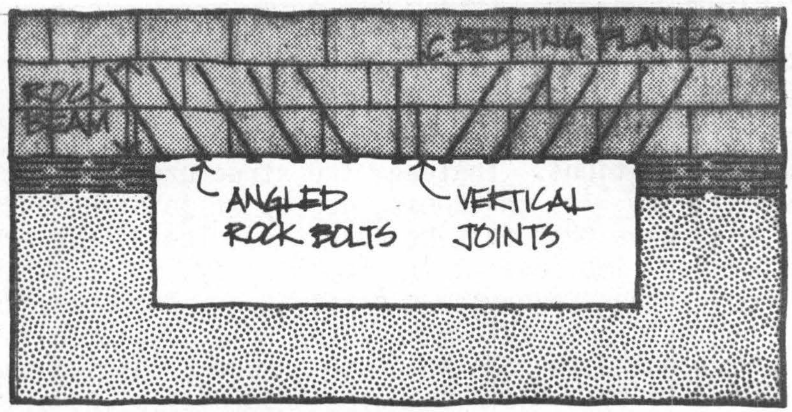
The design of the roof for mined space does not follow the normal process of structural design where the sizes of slabs and beams can be selected to meet loading conditions. Instead, the structural element of the roof is the limestone layer itself. Its thickness, degree of jointing and strength in any one location are parameters that must be accepted. The design process then involves checking whether the limestone in its local condition is capable of supporting itself and the above ground over the desired span. Improvements can be made to this ability and the most applicable method for this situation is to tie together layers of the limestone with rock bolts to ensure a unified beam of limestone of sufficient thickness to span the opening. These rock bolts also prevent any thin (6") layers from becoming detached from the underside of the roof. Where vertical joints are present, the 'beam' formed does not carry its load in the normal beam bending mode. Provided shear resistance on vertical faces is sufficient to prevent blocks dropping vertically downwards, the blocks must rotate as they attempt to move into the opening. The dimensions of the blocks and the presence of the surrounding limestone will not allow this, however, and the blocks become permanently wedged, bridging the opening with what is termed a linear arch or Voussoir beam. More substantial support to the rock is available in the form of steel beams, props and hydraulic jacks. These are used in tunneling and mining to provide artificial support where the rock cannot support itself. However, they are very expensive and would also infringe greatly on the size and flexibility of the underground space. It would undoubtedly be uneconomic to support more than a small percentage of underground space in this manner.

It is envisaged at present that 1" diameter steel reinforcing bars 8'-10' long would be grouted (cemented) into the roof on a 4' or 5' grid. The 4' or 5' grid patterns are a common practice in rock bolting and more design information would have to be collected before this could be increased. The bolts would be installed at an angle to insure intercepting vertical joints providing added resistance against shear failure on these joints (especially important at the edges of the excavation). This level of support is presently considered very adequate for the 50'-60' spans envisaged. Parking layouts have been worked out using a 60' span on the rib system; archive and other space on a 50' span room and pillar system. Prior to obtaining more conclusive evidence from the underground test room this is reasonable because the clear distance between supports at an intersection of the room and pillar system is approximately 70'. This compares with 67' for an intersection of a 60' span and a 30' cross-cut in the rib system.

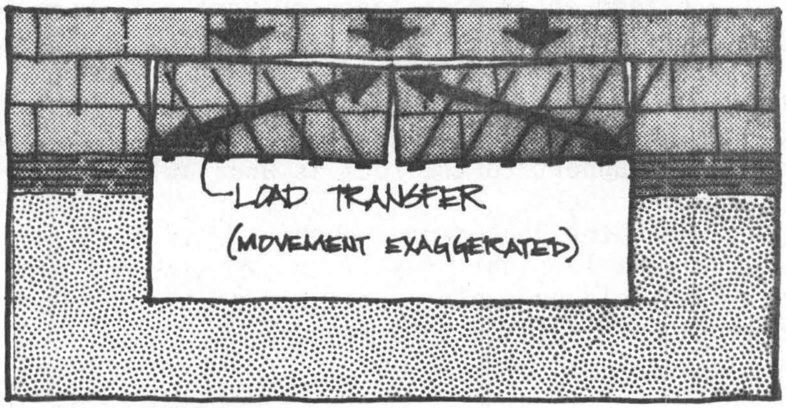
Because of the massive weight of the rock itself (1 ft. thickness of rock is equivalent to 160 lb/ft^2 loading ,i.e. a very heavy floor loading for a commercial building) weights of structural materials for an internal roof are insignificant compared with the weight of the rock. Hence, any waterproof ceiling installed below the limestone can be hung from the roof as can be any additional false ceiling for aesthetic or acoustical purposes. The provision of a waterproof ceiling is intended to catch the slight seepage that may occur through the limestone joints, divert it to the sides of the room where it can be collected and drained into the sandstone below the room or into storm sewer tunnels. Any larger flows, if encountered, could be reduced to these proportions by grouting the joints that are causing the problem.



resin grouted rock bolt



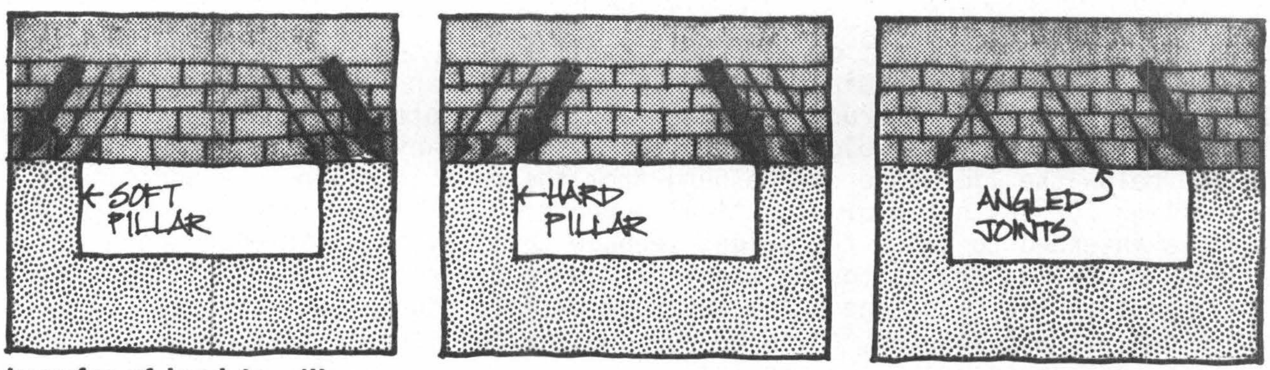
roof on completion of excavation



formation of linear arch

pillar and wall design

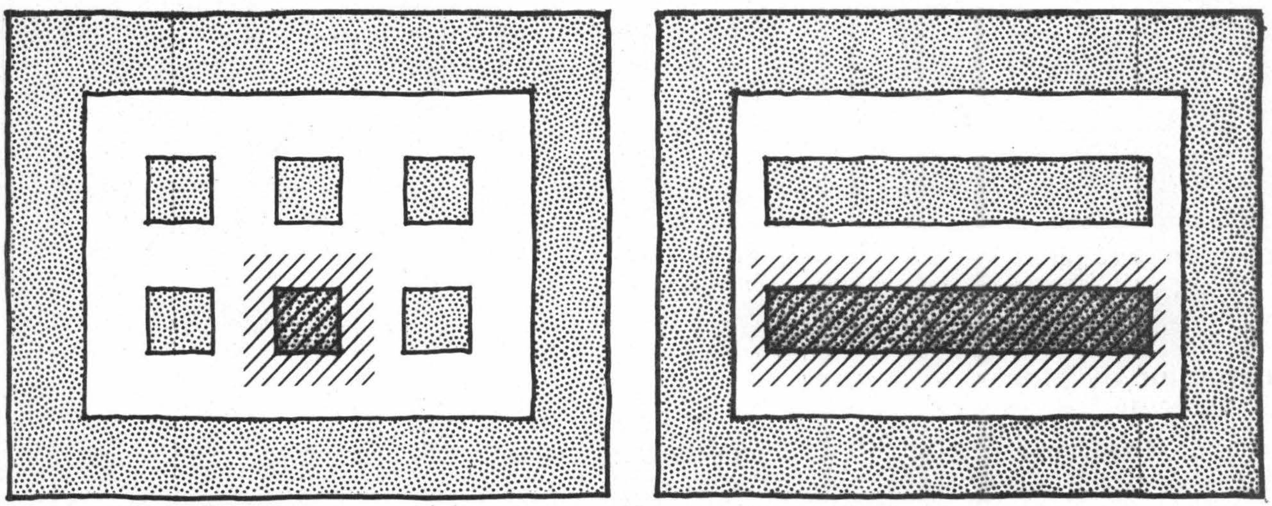
The walls of the mined space must be strong enough to resist sloughing into the excavation under their own weight and also to withstand the additional load that was originally carried by the excavated material. The total additional load to be carried is easily calculated as the weight of material above the opening. The distribution of this load, however, is very complex and depends on the relative deformations associated with compression of the rock formations, the orientation and degree of jointing in the roof and many other factors. If the load is mostly transferred to the immediate edges of the excavation, more problems can be expected than if the load is spread deeper into the rock mass.



transfer of load to pillars

As the mined space considered here is close to the surface, both the original and the final pressures on the walls of a single 50' opening will be low and the stability of the walls should not be a problem.

For larger units of mined space which involve leaving ribs or pillars, the approximate average increase of stress can be calculated by finding the extraction ratio for the system used. The extraction ratio is the ratio of the area excavated to the total area before excavation. For the room and pillar system with equal pillar sizes and spans the extraction ratio is 75% and hence the final average pillar stress approximately 4x the original vertical stress in the sandstone (since the pillars form 25% of the original area). For the rib system with equal spans and pillars the extraction ratio is 50% and hence the average pillar stress is 2x the original. The rib system obviously has a larger factor of safety at the expense of having to extend farther laterally to obtain the same amount of space. Since the rib system can be converted to a room and pillar system by widening cross-cuts through the pillars, use of the rib system as a first step to the room and pillar situation would appear to be prudent, at least on initial excavations of this type. The pillars could then be monitored as the load on them is increased by further excavation.



approximate areas of roof supported by individual pillars or ribs

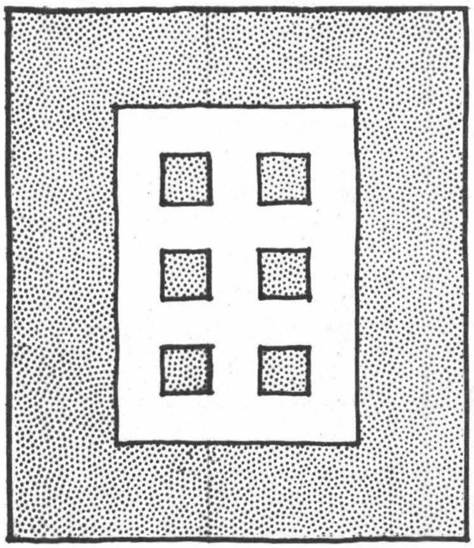
Another consideration in pillar design is the effect of the shape and size of a pillar on its load carrying capacity. Most of the research in this area has been concerned with pillars in coal seams. A range of results have been obtained by various researchers due to the different materials used and discrepancies between test procedures but a simplified relationship cited for the strength of a pillar is that:

$$S = K\sqrt{\frac{W}{H}}$$

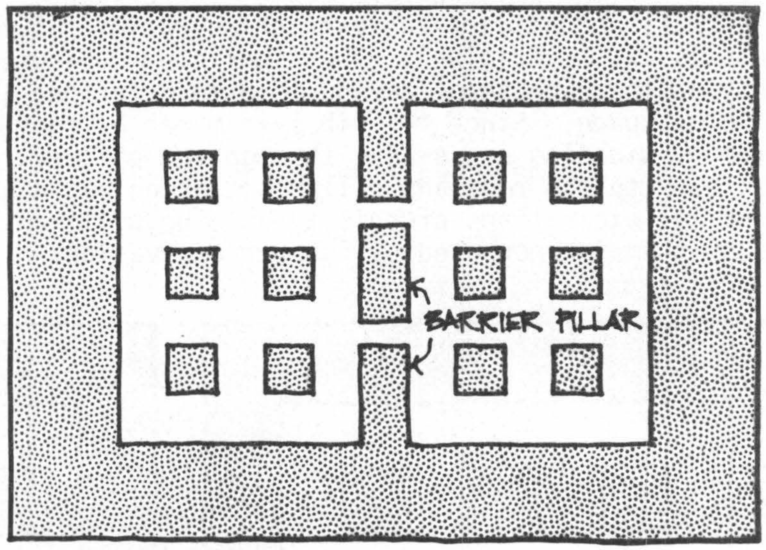
S = strength of pillar in lbs. per sq. in.
K = a constant depending on the nature and strength of the material
W = least width of pillar in inches
H = height of the pillar

This cannot be taken to be completely valid for sandstone but it does illustrate the probable relationships involved. If the pillar height is doubled without any change in width, the strength and the total load capacity of the pillar is approximately halved. To achieve the same load capacity the width of a square pillar must be increased about 30%.

As an added safety measure ribs should be incorporated at intervals in a room and pillar design to prevent an isolated pillar failure from providing a mechanism for the progressive collapse of other pillars.



small room and pillar system



expansion of system

construction of internal structure

Where portal access for construction equipment and trucks to be driven right into the mined space is provided, construction within the excavated room should be no more difficult than in normal situations. Delays due to the weather or protection from extremes of temperature will not be a problem underground. Because of this, consideration should be given to letting contracts for the winter months when contractors have the least work and are likely to bid the lowest. Access tunnels should be of sufficient width for two-way construction traffic and have normal roadway height clearances. Curves of intersections should allow long trucks to negotiate the turns without undue difficulty.

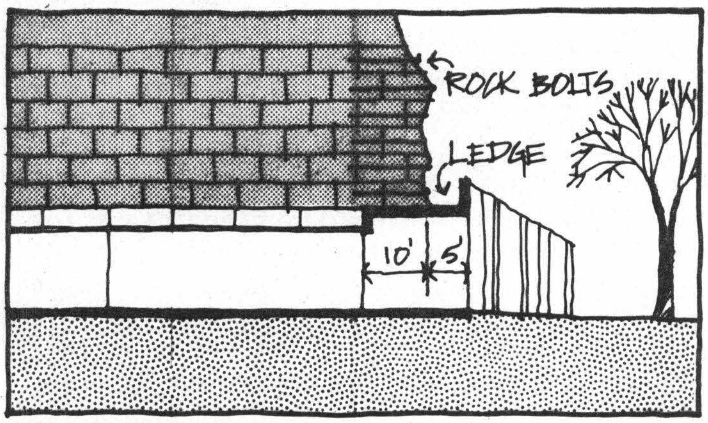
Forms for pouring the concrete walls could be supported by anchoring them into the walls or by bracing, but in view of the large area of wall of a repetitive nature, travelling steel forms should provide a much faster and cheaper solution.

In two level space it is desirable that the lower level allows the same degree of flexibility given by the clear span of the roof in the upper level. Precast T-beams or double T beams are available to span 50'-60' and where they could be brought in through portal access, the height of the cavern above the intermediate floor would allow tilting and raising the beams into position. Where such a system is not possible in-situ slab and column construction with a single central column would provide an alternative at approximately the same cost but reduced flexibility. Another possible solution is a poured-in place concrete beam and slab system that spans the entire bay. This type of floor system is more costly but may be the best solution when a clear span is desired and pre-cast elements are not feasible. When considering the erection of beams and formwork in mined space, it should be remembered that rock bolts in the massive limestone can provide substantial temporary support or lifting capacity. If columns were used for the internal structure, no special provision for foundations other than local reinforcing of the floor slab would be necessary since the allowable bearing capacity of the sandstone is very high.

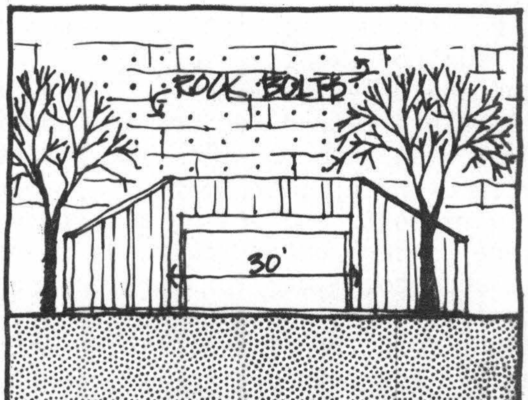
structure at portal

Additional structural treatment of mined space is necessary at the portal entrances in the river bluffs. Because the limestone is not confined on one side and because of the effects of erosion and weathering, the limestone is generally in poorer condition and more frequently jointed than away from the bluffs. To allow for this it is suggested that portal openings be limited to about 30' span and extend back into the bluff for at least 50' before widening or changing to the full scale room and pillar system.

A concrete lining should be applied to at least the first 10' of the portal access for increased stability and to prevent accelerated weathering in these areas. The lining should extend beyond the face of the portal incorporating a roof structure to catch small-medium size rocks and any shale or soil that may fall from the natural weathering processes on the bluff. The possibility of large rock movements should be prevented in the portal area by the use of long rock bolts to tie the rock mass together. These need not be obtrusive if fully grouted bolts are used since no bearing plates for the bolts would be required.



section of portal



elevation

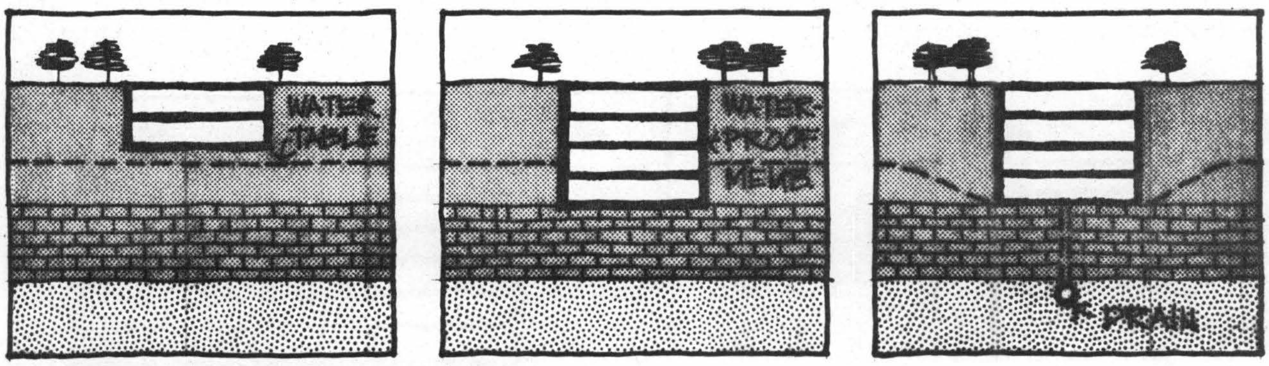
While cut and cover buildings in soil do not present any uncommon engineering problems, there exists a large variety of methods of constructing such buildings which can profoundly affect the performance and cost of the excavation and structure. A general discussion of this was made in the earlier report and some details will be presented here.

The common method of constructing deep basements of underground buildings in the University area at present is to use steel H-piles with wood lagging in-between for a temporary retaining wall incorporating tie backs for additional support. When the excavation is complete, the building is constructed within the excavation, allowing sufficient working space outside the permanent retaining wall for erection and dismantling of forms, applying waterproofing to the outside face, etc. When the building shell is complete to ground level, the temporary retaining wall is removed gradually as backfilling around the building proceeds. The tie backs are cut off at the surface and left in the ground. While this probably represents the cheapest system of temporary retaining for a normal building basement, there are some drawbacks to the method which should be considered. The excavated area is at least 4' larger all around than the exterior dimensions of the final building. This can become significant on smaller buildings. The steel piles and wood lagging are a relatively flexible retaining system and do permit some movement of the adjacent ground and often some loss of soil in wet weather. Adjacent to old or important buildings with shallow foundations the dangers of such movement are magnified. Finally, the process involves a great deal of wasted effort since the expensive temporary retaining wall is not incorporated into the final design.

Steel sheet piling differs from this type of construction only in probably allowing less ground loss but requiring more pile driving which is a noise nuisance in congested areas. Bored, cast-in place concrete piles, however, offer a different alternative. Reinforced concrete piles are cast in holes drilled in the ground at a close enough spacing to form a continuous wall. The drilling operation is quieter than for pile driving, the wall can function as both a temporary and permanent retaining wall and it can carry the load from any exterior above ground columns at ground level. It still requires bracing or tie backs but these can be incorporated into the permanent design. If waterproofing is required, the wall must be smoothed sufficiently to apply this and then a wall built within to withstand only the water pressure, the ground pressure being taken by the outside wall. This method reduces the possibility of the settlement of adjacent buildings. It has been incorporated with a construction sequence of casting the outer perimeter of each floor slab on the earth as the building is excavated (reducing formwork costs and acting as retaining wall supports). Consulting engineers for several underground structures constructed in this manner have claimed it to be fast and economical for deep basements. Diaphragm walls are the next step up in security against movement of adjacent buildings. They are constructed by digging a long, deep trench kept filled with a mud slurry to hold back the walls of the trench. The reinforcing is lowered into the trench and it is concreted by displacing the slurry out of the trench as heavier concrete is pumped through a pipe into the bottom of the trench. It is an expensive method of construction at present, but again does provide permanent as well as temporary support.

The cheapest and easiest treatment of excavation walls is to slope them. This is commonly done in the University area at a slope of approximately 1½ (horiz) : 1 (vert). Unfortunately, there is rarely sufficient area outside the building for this to be done on all sides. A 200' square building 50' deep would require at least a 350' square area for this to be done and would destroy any mature trees that might be saved with a retaining wall. Naturally, the best alternative is no treatment of the sides of an excavation and this can occur when a new building is constructed immediately against an older building extending to bedrock. This has already been done on campus with the phased construction of Health Sciences Units A and B-C. Since the temporary retaining wall cost dominates the cost of providing the excavation even in large areas, this represents a large cost saving in the excavation phase as well as the elimination of waterproofing and permanent retaining wall costs on that side of a building. Hence, consideration should be given in areas where future adjacent construction may occur of extending basements (probably of a larger size than the building itself) to the limestone to facilitate the future excavation as well as providing the immediate benefits of additional underground space.

Permanent retaining wall design will consist of a reinforced concrete wall whether built free standing inside a temporary retaining wall or cast against a concrete pile wall as discussed above. In either case, the walls are supported against lateral soil and water pressure by the floors in the building. The diagrams below illustrate methods of avoiding water problems. This is discussed further with reference to deep cut building. As the pressure increases with depth, large floor/ceiling heights should be avoided at depth in the soil except where large machinery required for servicing the building must be placed on the bottom floor due to its heavy weight.

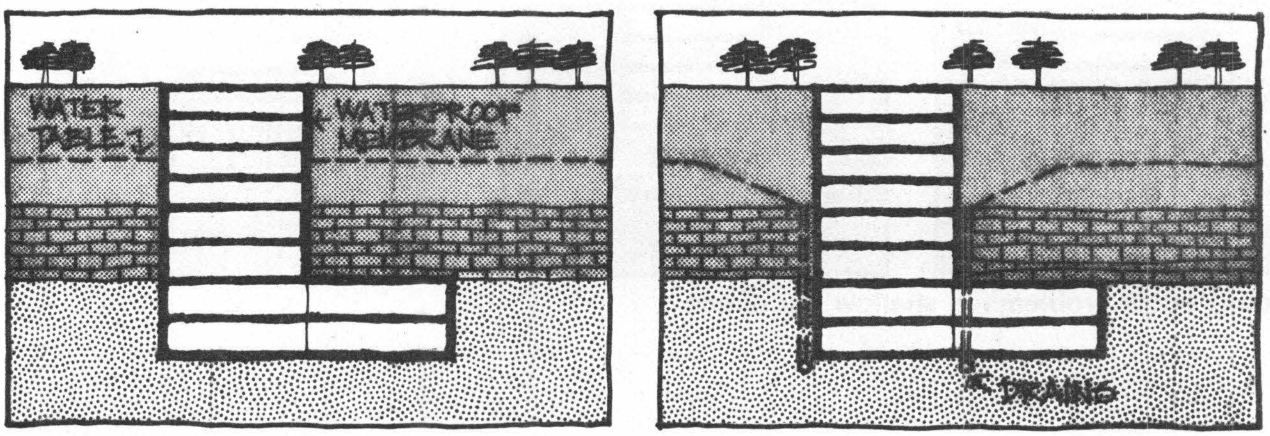


avoiding water problems in shallow cut space

deep cut and cover buildings

Deep cut and cover buildings extending through the limestone present some different problems to those discussed for shallow cut and cover situations. When excavating through the limestone, although it is more difficult to excavate the limestone, the sides of the excavation will stand with minimal support. The only probable treatments would be pre-splitting to obtain a smooth blasted face and rock bolting to retain any loose blocks. The sandstone is easily excavated and will also stand with little or no support. This means that the cost per cubic yard of providing the excavation will not greatly increase when extending a building through the limestone.

The presence of the perched water table complicates the decisions about waterproofing any cut and cover space and, in particular, any structure which will pass through the sealing layers of limestone and shale which prevent its connection with the main water table. The alternatives used for buildings extending to the limestone are either to apply a high quality waterproof membrane to the outside of the permanent retaining wall or to use less water protection and provide a free draining layer around and under the building which is drained to a storm sewer in the sandstone. This would also be used in deep space to avoid having to design for large water pressures. The problems with this method are that the free draining layer may clog with time, allowing the water pressure to build up anyway and that the effects of widespread depression of the perched water table cannot easily be foreseen. It may also interfere with the development of mined space in the area by creating a heavy water flow around the building. Having decided to waterproof the structure adequately and prevent free draining around the structure, the construction procedure in the limestone and sandstone should involve applying a smoothing layer to the sides of the excavation, applying the waterproofing membrane to this and casting the reinforced wall against this.



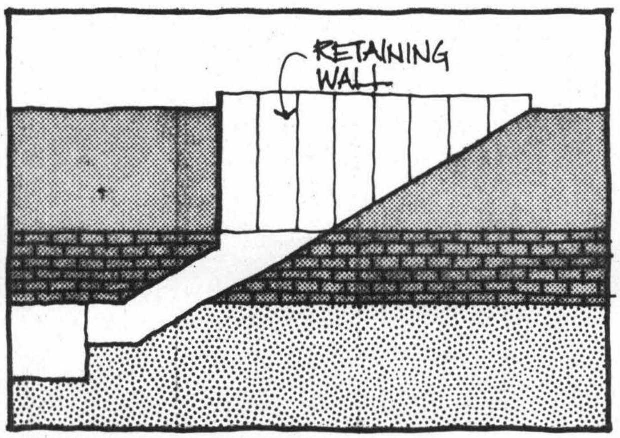
deep space waterproofing solutions

The practice of constructing the permanent wall free standing within the excavation would provide a free draining layer in the backfill and would not provide an easy transition to mined space. Grouting joints and fissures in the limestone adjacent to the building could also be used to limit the drainage if necessary. The transition from construction in the overburden to construction in the limestone can be easily made by keeping the exterior faces of the permanent retaining wall in line. A temporary retaining wall in the soil could then be provided at a sufficient distance from this to provide the necessary working space. This allows the waterproof membrane to be straight and continuous.

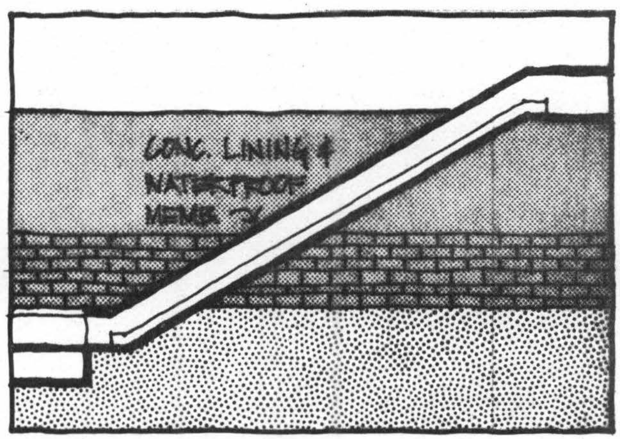
shafts

Shafts can be considered as miniature deep cut excavations and hence the comments on waterproofing versus draining made above are still applicable. Large shafts are constructed in much the same manner as deep excavations except that the working space is greatly restricted and that the soil is usually held back by bracing across the shaft or by using a circular liner plate. Large shafts must be blasted through the limestone but smaller shafts (under 10'-15') can be drilled. The drilled shaft is faster, provides a smooth wall to the excavation and does not damage the surrounding limestone. Up to 25' diameter shafts can be drilled through the overburden. Obviously, drilled shafts must be circular whereas blasted shafts can be circular or square. Circular shafts can be lined more cheaply since soil and water pressure are carried in direct compression of the concrete ring. Square shafts, on the other hand, while requiring design for bending in the walls, usually allow a more efficient utilization of the space provided.

Long diagonal shafts are required for escalators. In the overburden this would require construction of the shaft lining in a long deep trench followed by backfilling to the surface. The shaft could, however, be blasted at the required angle through the limestone. The construction of such a shaft would be very expensive and probably only justified for special intensive uses such as a transit station.



construction of elevator shaft



completed installation

4 mechanical considerations

introduction

Energy conservation is one of the principle attractions of underground space development. It is known from existing examples as well as intuitive estimates that substantial energy savings are possible. It has been shown that an underground manufacturing plant in Kansas City has operating costs that are less than 10% of a comparable above ground building. Unfortunately, consistent and reliable estimates of actual cost savings are quite difficult to pinpoint. One reason is that there are numerous interrelated and complex variables which affect the mechanical requirements of a space, making it extremely difficult to generalize from specific examples. Another reason is that some basic properties of underground spaces such as the rate of heat and moisture flow into the rock or earth are not yet well enough documented to be used for actual mechanical calculations. Nevertheless, we are presenting some hypothetical energy calculations in order to illustrate the magnitude of potential savings and serve as a basis for a discussion of the various factors affecting energy conservation. Following the figures, the various factors used in the calculations are presented and explained. Finally, this section concludes with a general presentation of heat flow characteristics underground, the shape and layout of underground space with respect to mechanical requirements, and long range cost figures.

comparison of surface/sub-surface energy use

heating loads

In order to compare the energy requirements of mined, cut and cover, and typical surface space, a unit of space has been selected (50' x 100' x 25' deep or 10,000 ft^2 floor area) and the heat losses calculated for each of the three locations at the winter design temperature of -20°F. The two major components of heat loss are the transmission loss through the building walls and the loss due to the introduction of outside air for ventilation. Since ventilation requirements depend on function, occupancy and other factors, the calculations were done for both a minimum and a normal ventilation level for typical university buildings. The ventilation losses are the same for all three types of space, while the transmission losses differ significantly. In the two level space used for these calculations, the transmission loss is a somewhat larger percentage of the total than in a larger multi-level space. For this reason, comparative heat losses for various sizes and shapes of buildings will follow in a later section. (The results of the calculations indicate total heat losses in cut and cover space from 20 to 30% less than surface space and losses in mined space from 30 to 40% less than the surface.)

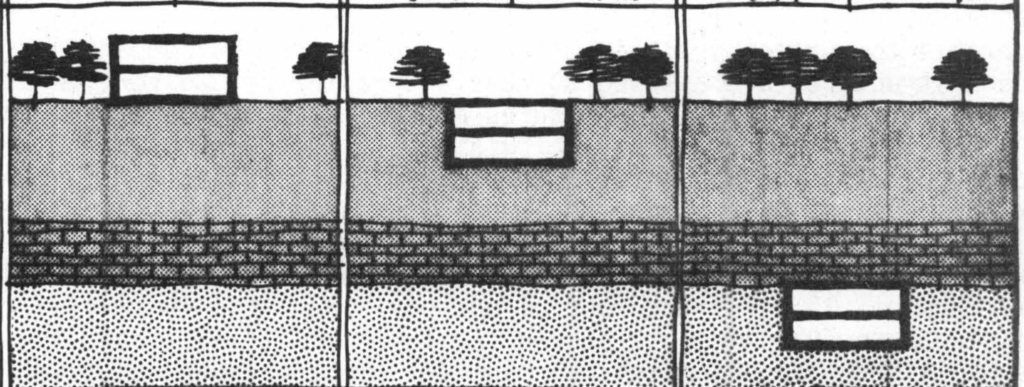
The internal heat gain due to lights and people have been added to the total heat losses to indicate a more realistic heat loss during the daytime. When the internal heat gain is included in the calculations, the percentages increase up to 60% in cut and cover space and 85% in mined space for 100% occupancy. Although these figures reflect significant savings, it is essential to note that they are based on assumptions which are quite variable. However, in this comparison the values that are generally most favorable to surface space and least favorable to underground space were used. It may be that the rather substantial savings indicated here are minimum values which can be improved upon with proper design.

cooling loads

In a similar manner to the heat losses calculated for the winter, the equivalent heat gains in summer for surface, cut and cover, and mined space are calculated here. The design temperature used for the peak summer load is 90°F. The same sizes of space, ventilation requirements and other values used to calculate heat losses are used in the cooling calculations. One notable difference between surface and mined space in the summer is that transmission through the walls produces a heat gain above ground and heat loss below ground. In determining the peak cooling load, the internal heat gains are added to the other loads. The results indicate about a 10% to 15% reduction in cut and cover space and 20% to 35% reduction in mined space with respect to surface space with 50% occupancy. When 100% internal heat gain is included in the calculations, the percentages are diminished slightly but underground space remains superior.

As previously stated, these figures are based on a number of assumptions and are taken for the peak load condition and cannot be considered as conclusive. However, they are indicative of the potential savings and serve to illustrate the magnitude of various factors involved. Following the calculations is an explanation of the values used and the various factors affecting energy savings.

heating	surface LOWER VENT. LOAD	surface HIGHER VENT. LOAD	cut & cover LOWER VENT. LOAD	cut & cover HIGHER VENT. LOAD	mined LOWER VENT. LOAD	mined HIGHER VENT. LOAD
transmission	195,000	195,000	79,000	79,000	35,000	35,000
ventilation (sens.)	145,800	291,600	145,800	291,600	145,800	291,600
ventilation (latent)	33,000	66,000	33,000	66,000	33,000	66,000
SUB-TOTAL	373,800	552,600	257,800	436,600	213,800	392,600
% REDUCTION			31%	21%	43%	29%
50% lights & people	-95,000	-140,000	-95,000	-140,000	-95,000	-140,000
TOTAL	278,800	412,600	162,800	296,600	118,800	252,600
% REDUCTION			42%	28%	57%	39%
100% lights & people	-190,000	-280,000	-190,000	-280,000	-190,000	-280,000
TOTAL	183,800	272,600	67,800	156,600	23,800	112,600
% REDUCTION			63%	43%	87%	59%



cooling	surface LOWER VENT. LOAD	surface HIGHER VENT. LOAD	cut & cover LOWER VENT. LOAD	cut & cover HIGHER VENT. LOAD	mined LOWER VENT. LOAD	mined HIGHER VENT. LOAD
transmission	36,000	36,000	7,500	7,500	-35,000	-35,000
ventilation (sens.)	24,300	48,600	24,300	48,600	24,300	48,600
ventilation (latent)	50,000	100,000	50,000	100,000	50,000	100,000
SUB-TOTAL	110,300	184,600	81,800	156,100	39,300	113,600
% REDUCTION			36%	15%	64%	38%
50% lights & people	95,000	140,000	95,000	140,000	95,000	140,000
TOTAL	205,300	324,600	176,800	296,100	134,300	253,600
% REDUCTION			14%	9%	35%	22%
100% lights & people	190,000	280,000	190,000	280,000	190,000	280,000
TOTAL	300,300	464,600	271,800	436,100	229,300	393,600
% REDUCTION			10%	6%	24%	15%

transmission

The heat loss which occurs by transmission through the exterior surfaces represents a major difference between surface and sub-surface space. It is based on the U-factors of the exterior surfaces and the temperature differential between the two sides of the surface. The cooling load presents a more complex set of variables. While above ground space is gaining heat through the exterior surfaces, below ground space is losing heat to the earth. The values used and assumptions made are presented in this section.

In the summer cooling load calculations the transmission load in surface structures includes additional heat sources such as solar radiation through the walls which is done by adjusting the actual temperature differential to a higher figure equivalent to these additional loads. Solar heat gain through glass can raise the cooling load considerably, but is not included in these comparisons. Even a building with 20% glass can have a peak cooling load 50% higher than a windowless structure. Any glass areas in surface buildings would only increase the relative energy savings found in underground space.

▪ U-factors

The values used in calculating transmission losses were selected to be particularly favorable to surface space in order to avoid a biased comparison. The above ground structures are assumed to have a U-factor of .20 for the walls and .10 for the roof and floor. The figures are quite good considering that no windows or doors were included in the calculations. Some windows are likely in any above ground building and would raise the transmission losses considerably. However for this comparison a windowless, well insulated space is used.

For cut and cover and mined space all exterior surfaces are considered to have U-factors of .10. For the roof of outdoor space this is similar to the surface building. However it might be reduced further with some additional earth covering. The walls and floor of a typical basement are considered to have a U-factor of .10. While the values used for the above ground structure are very good, the U-factor used below ground will probably be poorer than the actual condition, especially in deeper spaces. As in surface space, no windows or openings were included in cut and cover space for simplicity.

▪ temperture differential

The winter design temperature of -20°F and the summer temperature of 90°F represent peak load conditions for the Minneapolis-St. Paul area. Although these temperatures do not produce an accurate reflection of costs over a season, they are useful in demonstrating the magnitude of savings possible. They do reflect the possible reduction in equipment sizes for underground buildings.

For surface structures, the previously mentioned winter design temperature is used for the heat losses through the walls and roof, while a ground temperature of 40°F is used under the floor. In cut and cover space, the ground temperature under the floor is considered to be 50°F at a depth of 25 feet. The temperature differential for the walls is an approximate average of the above and below ground temperature 20°F for the first ten feet and then a constant 50°F for the remaining wall below 10 feet. In mined space, all the surrounding rock is considered to be 50°F. These figures are based on temperatures recorded below ground on campus and if anything are low rather than high.

The summer temperature differentials for surface space are based on data from ASHRAE. For example, for the roof at 2:00 p.m. the equivalent outdoor temperature including solar radition and other factors is 75° + 50° or 125° F. For cut and cover space the same figure is used for the roof, although the radiation in particular could be reduced by some additional earth cover. The ground temperature for the walls in cut and cover space is assumed to be 60°F while the floor is 50°F. Again, these values are conservative and the actual wall temperatures may be lower. In mined space, the surrounding rock is assumed to be 50°F year round.

ventilation

The heat losses or gains due to the introduction of fresh air into an occupied space usually comprise a major portion of the total load. It has been speculated that any energy saving potential of underground space would be offset by the required ventilation load. While minimizing ventilation requirements certainly enhances the energy savings potential of any space, underground space is by no means dependent on extremely low ventilation requirements to provide substantial reduction in energy use. Two reasonably standard levels of ventilation reflecting different occupancies have been selected and the three types of space are compared in both cases. The actual figures and assumptions used are presented here. In addition, awareness of the need for energy conservation has produced new developments such as energy recovery systems and changing code requirements for ventilating. All of these are equally applicable above and below ground but they increase the relative impact of energy savings underground.

▪ assumptions

The ventilation load depends on the total occupancy of the space and the amount of fresh air per occupant. The lower level selected for the examples is 50 ft^2 of floor area per person maximum occupancy with 7.5 cfm per person outside air (or 100 ft^2 per person with 15 cfm per person outside air). This would be an adequate level of ventilation for many functions including office space, many laboratories and libraries; more than adequate for various storage and service areas. The higher level selected for the examples is 25 ft^2 per person maximum occupancy with 7.5 cfm per person outside air (or 50 ft^2 per person with 15 cfm per person outside air). This level of ventilation would be adequate for classrooms, meeting rooms, and most lounge, eating and recreational areas. At the overall requirement of six air changes per hour, the lower figure for outside air represents 15% of all the air circulated and the higher figure represents 30% fresh air.

An underground parking garage would require substantially more outside air but it would not need to be heated or cooled to the same level so it cannot be included in this comparison. The energy used for simply ventilating is rather small compared to heating and cooling. However, the cost of the ductwork and the entire mechanical system is a cost that would not exist in an above ground parking structure.

▪ infiltration

In order to make a fair comparison between above and below ground space, the extra load of heating or cooling air introduced by infiltration is ignored. This is because this load can vary considerably and is somtimes eliminated by ventilation under pressure. In underground space, infiltration is almost negligible compared to the surface. Any infiltration at all that occurs in above ground space would result in an additional load and represents another significant advantage of below ground space.

■ **future trends**

Although the figures presented in this comparison are based on standard ventilation loads, there is the possibility of revision of the existing codes resulting in a lowering of ventilation requirements. Concern over energy conservation has led to the realization that some requirements for outside air can simply be reduced or that by additional filtering of recirculated air, a reduction in fresh air can take place. Optimizing existing technology can result in substantial savings. These trends are important because any reduction in the ventilation load greatly enhances the relative savings in underground space.

■ **energy recovery**

One energy conserving device which reduces the ventilation load substantially is a heat exchanger or energy recovery system. In winter the warmth of the air being exhausted from the space is transferred to the cool outside air being taken in. With a system such as this from 30 to 60% of the energy lost through ventilation can be recovered depending on the design and efficiency of the device used. Again, this type of saving would greatly complement the other advantages in below ground space.

■ **humidity**

In addition to raising or lowering ventilation air to a comfortable temperature which is reflected in the sensible ventilation load, the air must be brought to a comfortable humidity level as well which is reflected in the latent ventilation load. The latent loads presented in the calculations are based on standard practice of raising outdoor air to 30% R.H. in the winter and lowering outdoor air to 50% R.H. in the summer. If the underground space is well sealed against moisture, these loads should be the same above or below ground. It is possible, however, that a higher level of humidity may be found underground and not be so high that complete moisture protection is necessary. In this case, the latent ventilation load in the winter could be reduced since incoming air would not need to be humidified as much. It is likely that any savings made in the winter would be more than offset by greater dehumidification requirements in the summer.

internal heat gain

The internal heat gain due to lights, people, and mechanical equipment is another variable which can have a significant effect on the heating and cooling loads of a space. This internal heat is not necessarily a constant load and obviously depends on the specific use of the space. While it would be considered part of the peak load for cooling in summer, it may not be counted on to help offset the peak load in winter. For the purposes of our calculations, it was sufficient to select a standard lighting level of 3 watts/ft^2 which produces about 10 BTU/hr per ft^2. Then for the two levels of occupancy previously described, it was assumed that each person contributed 450 BTU/hr heat gain. So for the two level space with the lower occupancy figure of 200 people (50 ft^2/person), the internal heat gain is 90,000 BTU/hr for the people and 100,000 BTU/hr for the lights. For the higher occupancy level of 400 people (25 ft^2/person) the gain is 180,000 BTU/hr for the people. These figures reflect the absolute maximum. Therefore, a figure for 50% of the lights and people is indicated and may reflect a more typical situation. In many circumstances, the internal heat gain can go beyond offsetting the heating load and actually create a need for cooling in the middle of winter. The implications of this are quite important in determining energy costs.

▪ heat gain balance

The figures shown for heat loss totals are calculated at -20°F. The internal heat gain can help to reduce the load but does not offset the heat losses at this temperature. However, at a somewhat higher temperature the gains equal or exceed the losses, and it becomes necessary to add no new heat; in fact, the space must be cooled even though the outdoor temperature is well below room temperature. It is possible in this situation to cool the space using outside air for the relatively small energy cost of operating the ventilating equipment. This would require an ability to provide a variable volume of outside air depending on the quantity needed to cool the indoor space. This possibility means that the heating requirements during winter could be limited to only certain times of the day and to only rather low temperatures when there is a substantial internal heat gain.

For the relatively well insulated above ground space used in the examples, a high internal heat gain (100% lights and people) can offset the heat losses when the outdoor temperature is in the range of 20°F to 30°F. For cut and cover and mined space the heat losses can be offset by the same internal heat gain at 0°F to 10°F. In some circumstances of high internal heat gain, mined space can be shown to require heat only at the most extreme winter temperatures. These facts amplify the potential energy savings with underground space during the heating season. In addition to having smaller heat losses at any given temperature, heating can be eliminated in underground space at a temperature about 20° lower than the corresponding temperature in above ground space. Thus the length of time heat is required can be significantly reduced in spaces that have constant substantial internal heat gains.

heat flow characteristics

The actual heat flow characteristics of a space surrounded by earth or rock are quite different than those of a space enclosed by a conventional building skin. The heat loss or gain through a typical building is in a steady state condition with a predictable constant rate based on the insulation value of the material and the temperature difference. A space surrounded by earth would lose heat to the earth but as the earth absorbs heat, the temperature of the earth would rise and the heat loss would diminish. This process could take a long period, even a few years, before some predictable steady state is reached.

The calculations of heating and cooling loads at the beginning of this section do not take into account these characteristics and it is difficult to properly include them at this time since little experimental data is available. However, the implications of this gradual warming effect are obvious. In the winter, even less heat loss due to transmission would occur underground than is indicated in the calculations. It should be carefully noted that the examples reflect a worse heat loss than will be found in sub-surface space after a short period of time. If a higher ground temperature were sustained year around, the cooling load would be increased but it would still remain less than above ground space. It is possible that heating would be almost eliminated with cooling and humidity control becoming the only substantial loads underground. Under these circumstances it would be of great importance to cool the space as much as possible by introducing outside air, thus providing no sensible heat load during most of the year. Many energy saving devices are applicable above or below ground but the unique heat flow characteristics of the underground are impossible to duplicate with surface construction and they further enhance the overall energy saving potential of the sub-surface.

heat retention and thermal mass

Another closely related characteristic of underground space is its high thermal mass which is the ability to store heating or cooling for release during a later time period. In space covered by earth, heat gain caused by high summer temperatures during the day is stored in the thermal mass or earth surrounding the building and released at night into the atmosphere. In mined space, the surrounding rock is virtually unaffected by surface temperature changes. In the winter, the space can "coast" for longer periods of time due to its ability to retain heat after any heat sources have been shut down. The cost and energy savings due to this ability to retain heating or cooling can be substantial. The tables on the following page illustrate the comparative differences between high and low thermal mass buildings and are taken from a study prepared for the National Science Foundation and the New York Schools System by Richard G. Stein. (The graphs are for a slightly higher temperature range then Minnesota's. However, they are only intended to show trends, not actual conditions.)

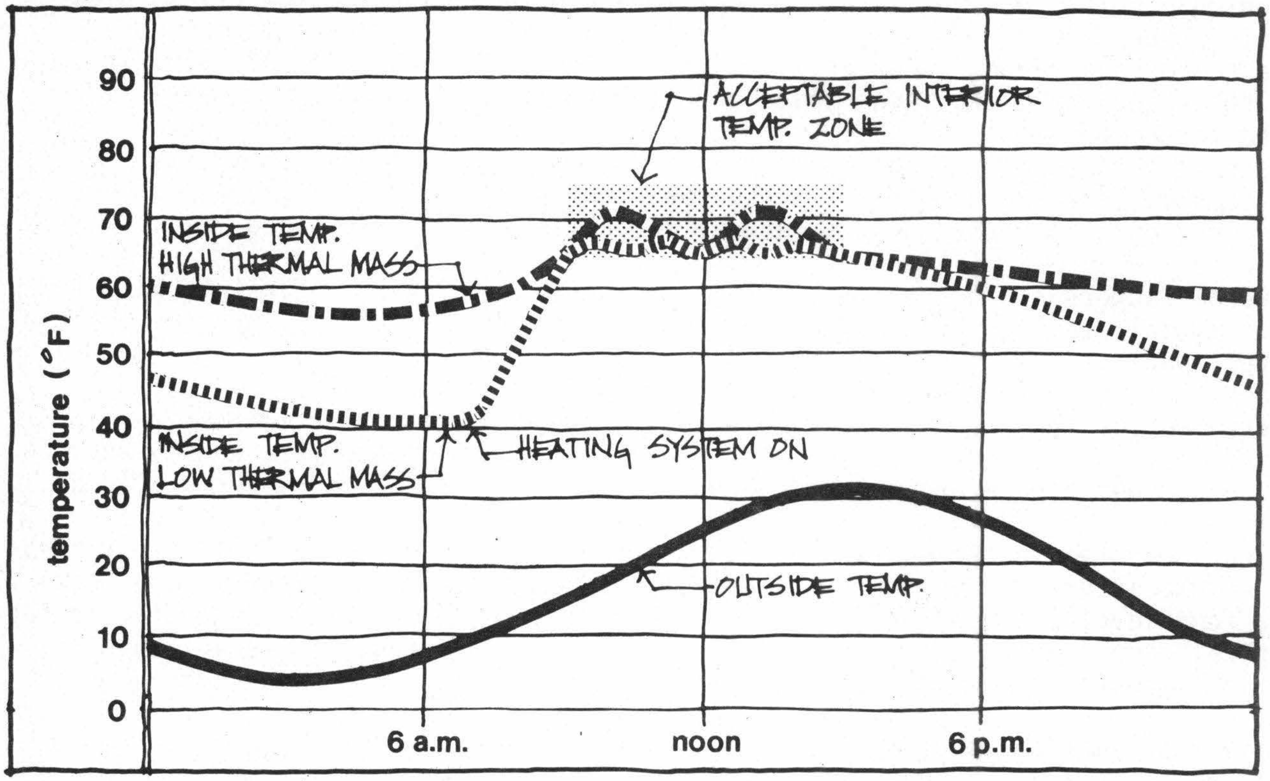
There are two basic ways in which this ability to retain heating or cooling can result in cost and energy savings. One is the obvious ability to shut off the mechanical system overnight and "coast". In a surface building this can be done but a large load must be taken care of in the morning since the building temperature has dropped or risen significantly overnight. Below ground, the temperature change would be slight which means the total energy costs might be reduced by one-third to one-half.

The second way to use this ability to retain heat underground for cost savings is to heat or cool spaces during the night when there is reduced rate for off-peak load power. This, of course, depends on the local conditions and sources of energy. However, this concept has worked in the previously mentioned Kansas City underground factory. Undoubtedly, overnight heating or cooling and "coasting" during the day would be more appropriate for certain uses with lower ventilation requirements than others. Nevertheless, it represents another possible way of using the unique thermal characteristics of underground space.

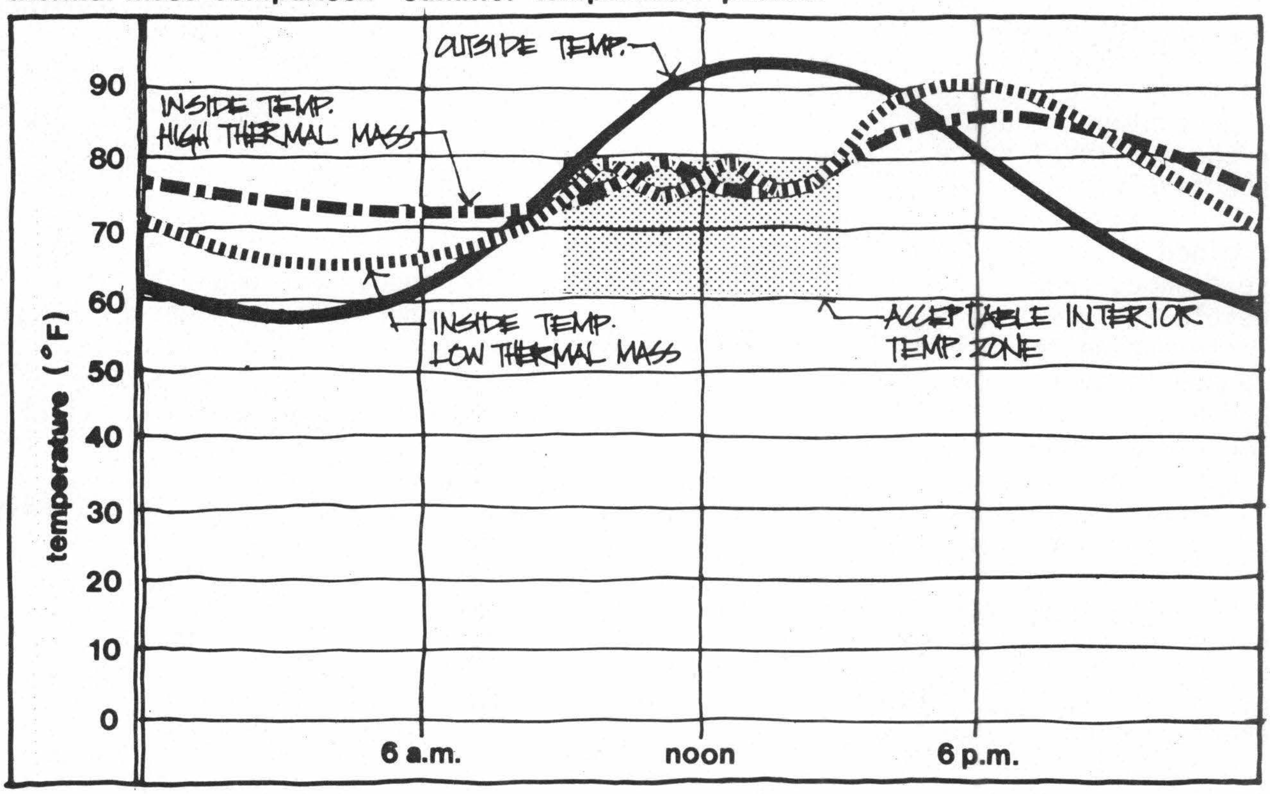
effect of shape and layout on energy use

In any building design the shape and layout of the building has a significant impact on the energy requirements. By minimizing the surface area exposed to transmission losses or gains, the loads can be reduced. The greatest volume with least surface area can be enclosed in a sphere, but since most buildings are rectilinear in form, the shape with minimum surface area is a cube. This definitely holds true for surface structures, but underground space presents different thermal conditions and some unique limitations to the physical layout that influence these energy requirements.

In the comparison previously presented for surface, cut and cover, and mined space, a 50' x 100' x 25' unit of space was used for the purpose of illustration. Undoubtedly, different shapes and amounts of space would produce different results. In order to evaluate our initial results as well as present some effects of shape and layout on energy requirements, we have chosen to compare the three types of space for various sizes and shapes. It is not necessary to compare the spaces under every condition of ventilation and internal heat gain so for simplicity the figures given are for the total heat loss at -20°F with the lower ventilation requirement (15% outside air) and no internal heat gain. The initial thermal mass comparison - winter temperature pattern



thermal mass comparison - summer temperature pattern



volume of space (a) is doubled to four levels (50' x 100' x 50') -20,000 ft^2 and then quadrupled to eight levels (100' x 100' x 50') 40,000 ft^2 which gives three basic shapes and volumes within a normal range. In the case of mined space, the same shape cannot necessarily be duplicated due to the physical limitations of the space, so a two level space equal in volume to the other examples is used for comparison. Actually, the transmission loss is greater for the mined space in this configuration than it would be in the 4 and 8 level shapes. Obviously, more extreme examples would give more dramatic results but for the purposes of this report only a general indication of trends is required.

Several factors can be noted as a result of this comparison. First of all, the substantial reduction in heat loss found in the earlier calculations for the two level space is also found in the other building shapes and volumes used in the example. In the case of cut and cover space the energy savings are further increased for the larger spaces compared to the surface, while the savings in mined space are slightly diminished. This seems to indicate that energy savings in underground space are not dependent on a particular configuration or layout.

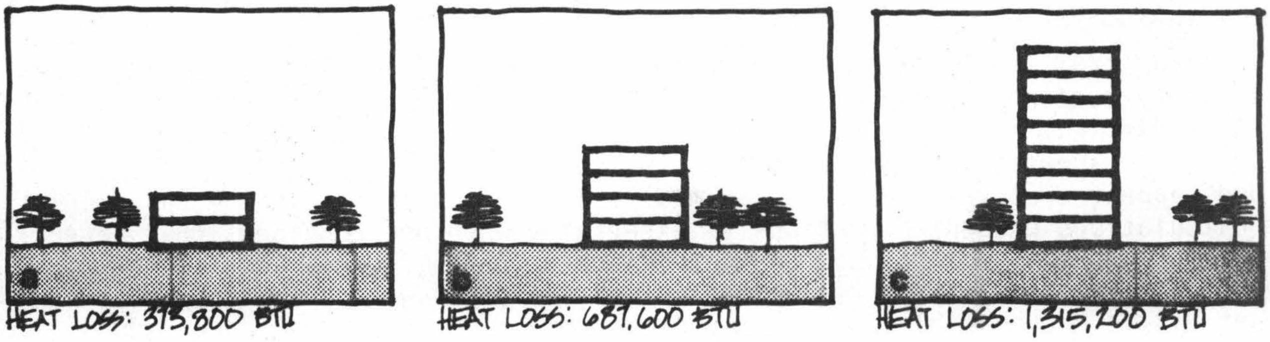
It can be noted in the surface structures that the heat loss per unit floor area or volume is greater in the two level structure due to its flatter shape. Both the four level and eight level examples are more compact shapes and better reflect typical campus buildings in size and shape. A taller structure would begin to reflect greater losses per unit volume.

Similar to surface space, a reduction in heat loss per unit volume is found in cut and cover space in examples b and c due to the more compact shape. However, there is a further reduction due to the fact that the ground temperature increase with depth until it reaches a constant 50°F at about 15' - 20'. Therefore, the two level space has a greater proportion of its wall surfaces near the surface subject to temperature fluctuations than the deeper four and eight level spaces. Even though the surface structures in examples b and c are relatively compact, the percentage reduction in heat loss for cut and cover space increases from 31% for the two level space, to 34% and 36% for the four and eight level spaces respectively.

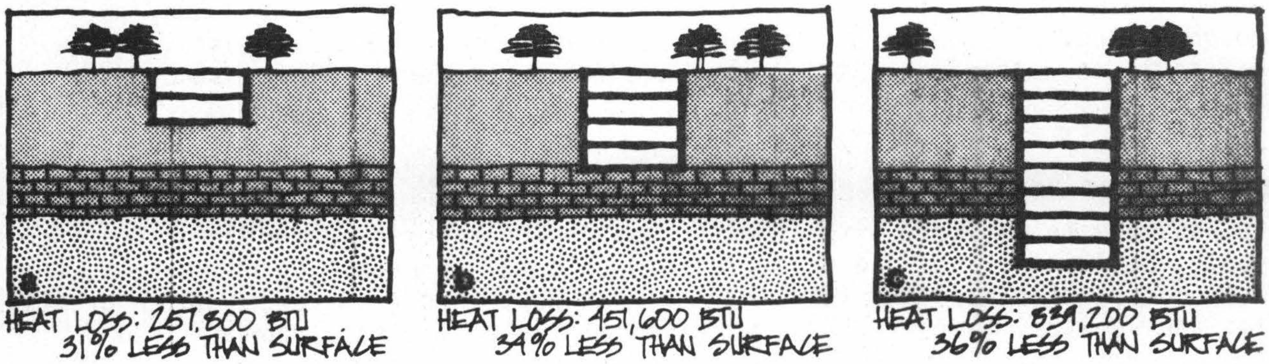
For mined space, the same kinds of comparison cannot be clearly made since we have assumed that a four or eight level structure in mined space would be unfeasible at this time mainly due to the level of the groundwater. However, it is interesting to note that when a volume of rather spread out mined space is compared to an equal volume of rather compact surface space, the mined space still represents considerable energy savings. The 43% reduction in heat loss found in example a is only diminished to 38% and 36% in examples b and c. Also, it should be noted that the mined space was assumed to have an equal steady loss through all the walls, whereas in reality the walls of the interior pillars would probably warm up somewhat rapidly and reduce the heat loss.

All of the calculations here are based on the assumptions used in the initial heating and cooling loads at the beginning of this section. Even though they are subject to change, we feel that they reflect the relative energy savings above and below ground, especially considering that many advantageous thermal characteristics of underground space have been ignored in the calculations.

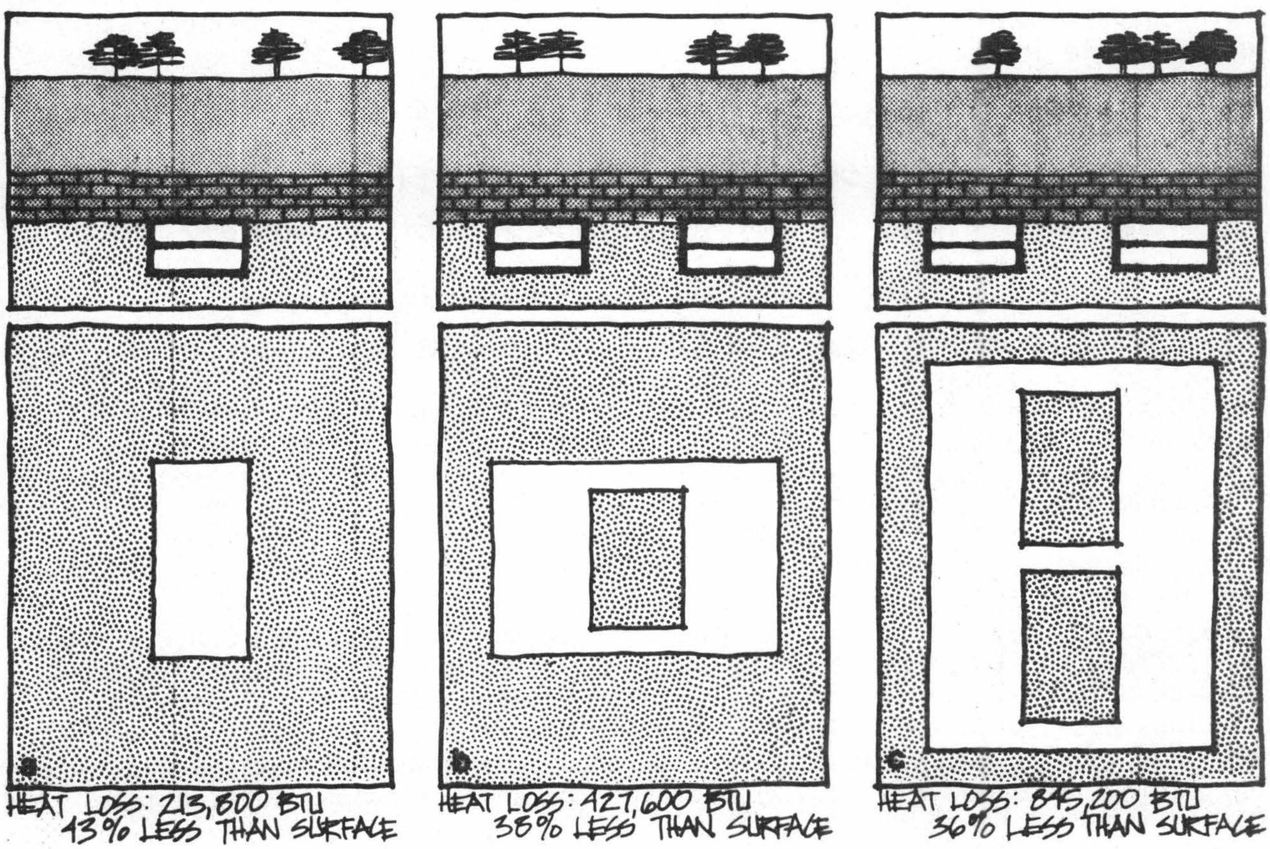
surface



cut and cover



mined



long range costs

It is clear from the number of variables and assumptions involved in calculating preliminary heating and cooling loads, that any long range costs and comparisons would be difficult to make with any reliable accuracy. Other factors such as the cost and accessibility of energy in the future are quite uncertain as well. It does appear that very definite savings result in sub-surface space based on the calculations presented previously, especially when one considers that several advantages of underground space are not included in the figures such as the high thermal mass and ability to retain heating or cooling. Within the scope of this report, it is not possible to provide an accurate cost analysis of year round energy requirements due to the lack of basic data and only a few existing examples. However, some extremely simplified figures can be presented as a means of demonstrating the magnitude of savings and illustrating a few important concepts. Although an accurate comparison of initial costs of equipment and installation is difficult to determine at this time, the factors affecting the cost are presented.

heating season comparison

It is possible to estimate with some success the energy requirements for heating a typical building by the use of degree-day data for an area. Unfortunately, this type of calculation does not take into account certain circumstances which greatly affect the results. Nevertheless, we have calculated the total energy used for heating from November 1 to March 31 for the three types of space based on our previous calculations and the degree-day data for Minneapolis-St. Paul. Only the five coldest months are used because the degree-day figures more accurately reflect the load in this period.

SURFACE SPACE:	636,245,000 BTU
CUT AND COVER SPACE:	494,091,000 BTU (22% less)
MINED SPACE:	421,931,000 BTU (32% less)

for two level space with lower ventilation load and no internal heat gain for 151 days from Nov. 1 to Mar. 31

These figures indicate a saving of over 20% in cut and cover space and over 30% in mined space compared to well-insulated surface space. However, two major factors are not included here and contribute heavily to reducing the heating costs of underground space even further.

First, the degree-day total is based on the difference between the average daily temperature and 65°F, ignoring the effects of internal heat gain. It has been previously noted that due to internal heat gain no heat is required above 20° to 30°F in surface space and above 0° to 10°F in underground space when the space is fully occupied. This fact changes considerably the value of the degree-day calculations because in the winter the daytime temperature is usually above 0° to 10° F but usually below 20° to 30° F. Without exact weather data, actual percent savings are impossible to predict but the savings appear substantial. With lower internal heat gain, more heating will be required but there will always be a lower cutoff point below the surface than above, making the actual heating time somewhat shorter underground.

The second major factor which affects the total energy use over the heating season is the heat storage capacity of underground space due to its high thermal mass. If the heating and ventilating system can be shut off overnight with no great drop in temperature, perhaps 50% of the total heating costs could be eliminated. Of course, this practice can result in some savings on the surface but they would be closer to a 20% reduction in a well-insulated building based on some existing experiments.

Using these rather crude figures and assuming all types of space are shut off overnight, the energy savings over the heating season becomes 50% to 55%. This is still not considering that the earth surrounding deep underground space may warm up over a period of years so that virtually no heating is needed at all.

These dramatic figures definitely represent cost and energy savings underground. However, they must be balanced against other cost factors to determine relative importance.

cost of system

The cost of the mecahnical system in an underground space is dependent on the load requirements as well as other physical considerations. Since the heating and cooling loads will be less underground, the central equipment can be reduced in size compared to a surface structure. However, the ductwork and air handling equipment would remain equivalent in size. In the University area heat and some other utilities are delivered through deep tunnels, making them more accessible to underground space. For mined space, additional cost is likely to be incurred by long intake and exhaust ducts to the surface. As previously mentioned, any ventilation system required for parking would represent a cost not found in most surface parking structures. Also, any special ventilation requirements such as large exhaust vents in the case of fire may be costly. In most cases, the installation of systems would be similar to any above ground space but any unusual circumstances or spaces with limited access would most likely increase costs.

special considerations

There are certain special considerations in designing mechanical and electrical systems for underground space which should be noted. These are primarily important in mined space and deep cut and cover space since shallow cut and cover space functions as a conventional structure in most respects. These considerations fall into two basic areas--the general planning of the mechanical equipment and special features required for emergencies such as fire. In the general planning, the most obvious feature is the additional ducts and equipment required to ventilate space as much as one hundred feet below the surface. Mechanical layouts must be planned with the shafts and portals since access to the space is limited to few points. In addition, larger ducts and air handling equipment will be required to move air over the longer distances. The second area of special consideration concerns features required for emergencies. An alternate power system will be required for underground space in emergency situations. Also, in case of fire additional emergency ventilation shafts for smoke removal may be required. Finally, underground space may require a drainage system for the space capable of handling a certain volume of water used to extinguish fires. These features are details to some extent but are mentioned since they represent a departure from conventional practice.

5 preliminary cost estimating data

introduction

One of the objectives of this report is to provide as much cost information as possible in order to determine the feasibility of underground space. For mined space there is very little in the way of actual cost data since virtually no comparable construction has taken place. For cut and cover space there are some actual construction costs available, however they are usually limited to fairly shallow excavations and generally applicable costs are not completely clear. However, for both types of space certain projections and assumptions can be made for the basic construction cost components which should be adequate for preliminary feasibility studies. These are presented in the preliminary costs section and are used in the following section on cost comparisons to indicate some basic relationships in design and planning of underground space. In addition to these general examples and comparisons, the cost data is applied to some specific examples mainly in mined space within the University area. These specific examples are not intended to represent design proposals but simply to illustrate the cost estimating procedure and to present factors in planning underground space in the campus site area. Finally, an analysis of costs over the life of a structure is presented in reference to underground space.

The cost of constructing underground space is obviously dependent on the function of the space, the quality of materials used, and the specific features of the design. In order to supply cost data which is applicable to a variety of uses and conditions, the costs are separated into two types. The first are those which comprise the basic unfinished shell and are part of any sub-surface development such as the excavation, structure and exterior lining of both mined and cut and cover space. The cost of shafts, portals and vertical circulation are also included in these basic costs. The second group of costs referred to as "Remaining project costs" are those which are common to any type of construction and vary considerably depending on the use of the space. These include interior partition walls, finishing costs, and mechanical-electrical systems. Some miscellaneous costs such as site work are quite variable and are discussed in general terms.

The intent of this method is to provide a cost per square foot of unfinished mined or cut and cover space and then provide the typical cost per square foot of finishing, mechanical-electrical, and miscellaneous costs for various uses of the space. In the sections on cost comparisons and illustrative examples which follow these figures will be used to indicate total costs and cost relationships. These costs cannot be regarded as definitive but they should serve for preliminary feasibility studies and are designed to be easily adjusted to a variety of conditions or as new information becomes available.

Unless otherwise stated, all costs are assumed to be for mined space with portal access for trucks and construction equipment. In addition, all costs include subcontractors' overhead and profit as well as 10% for the general contractors' overhead and profit. All costs have been adjusted to 1975 levels.

excavation

▪ sandstone

Since the sandstone is relatively easy to excavate, the main criteria affecting excavation costs are the ease of access for large construction equipment, the amount and type of temporary support required and the ease of removing the excavated material. In a small tunnel only one operation can be done at the face at one time, causing idle work crews much of the time. Also, large equipment cannot be used forcing inefficient methods of excavating the sandstone. When tunnels are excavated from a shaft, the material must be excavated, carried to the shaft, lifted up the shaft and finally loaded into trucks for removal. If hydraulic methods of cutting the sandstone and pumping a slurry of the excavated material up the shaft is used, the slurry must be separated for disposal into solids and a sufficiently clean effluent to meet pollution control standards.

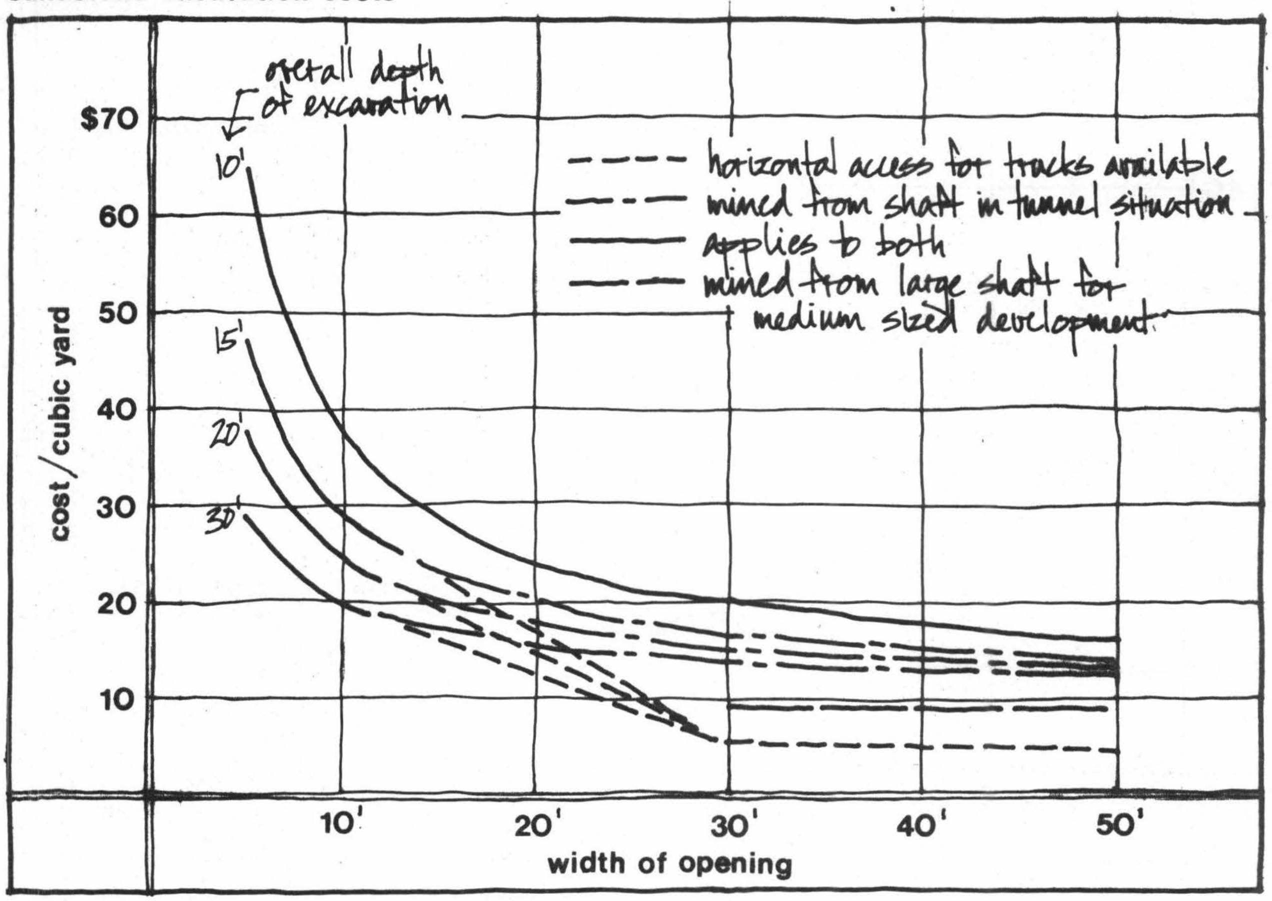
To cover the change in costs for different sizes of tunnel excavated from a shaft, a curve previously compiled and fitted to national data was used. This curve was adjusted to represent the lower excavation and support costs for sandstone tunnels by adjusting the curve parameters to fit two recent tunnel projects in the sandstone for which cost data was available. The final curve obtained is

$$\text{cost/cubic yard of sandstone excavation} = \frac{\$100}{\text{total no. of cu. yds. per ft. of tunnel}} + \$11$$

This basic curve is split into the four different curves shown on the graph for different heights of sandstone excavation. It is assumed that for tunnels less than 10' wide x 10' high the costs remain on these curves even when horizontal access is available.

When horizontal access is available for openings of 30' and wider and at least 15' high, a very different situation occurs. Large construction equipment can excavate the sandstone at the face and load directly into trucks which have room to turn around and pass each other within the tunnel. In this situation the costs are taken to be $5.50/cu yd at 30' wide dropping to $4.40/cu yd at 50' wide. For widths intermediate between 10' and 30' linear interpolation is used. A final category is when a mined space development is opened up from a shaft. In this situation a large shaft would be required for the final use and hence, reasonably large construction equipment could be lowered to carry out the mining. The fact that the excavation is not all in one long tunnel removes the bottlenecks associated with tunnel construction and also reduces the haulage distances underground. For this situation the cost is estimated at $8.80/cu yd. The graph of costs is shown below and it should be remembered that these are intended to apply to a reasonably large contract against which any capital costs of required equipment could be offset.

sandstone excavation costs



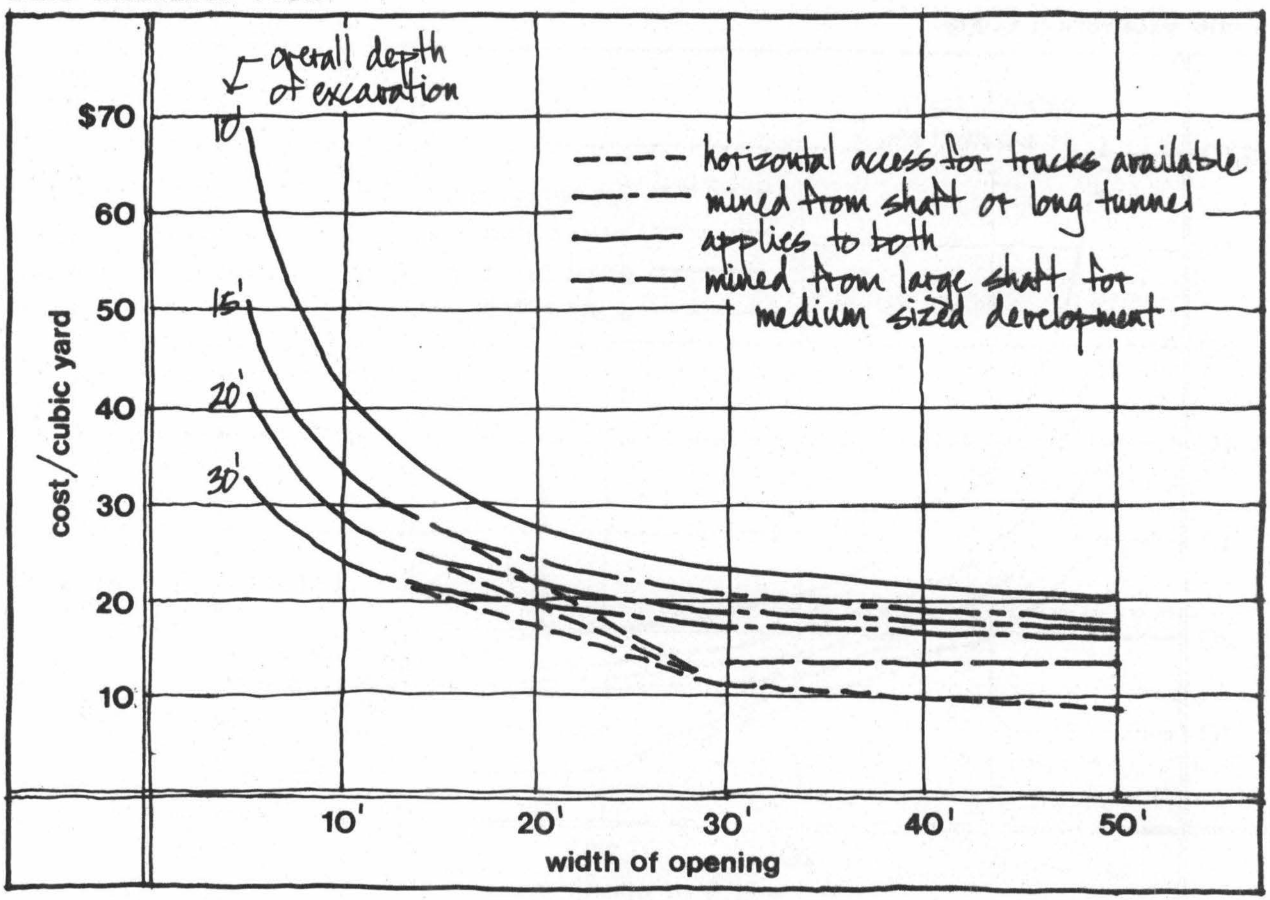
▪ shale

A similar diagram is used for the shale excavation. The tunnel cost curve is adjusted to reflect the increased difficulty of excavating the shale. The assumed curve is

$$\text{cost/cubic yard of shale excavation} = \frac{\$100}{\text{total no. of cu yds. per ft. of tunnel}} + \$15$$

Where horizontal access is available, the effect on costs is taken to be much greater since it was assumed that a large excavator would mine and load the sandstone in one operation, whereas the shale would require mining with a special purpose machine such as an Alpine Miner followed by separate loading. The costs for shale are assumed to be twice the sandstone costs in this situation. For mined space development from a large shaft the cost for shale is assumed to be 50% greater than for sandstone because the costs already allow for some multiple handling.

shale excavation costs



▪ summary

In the cost comparisons and examples which follow, all typical mined space is considered to be 17' high for one level space and 30' high for two levels. In both cases, the upper 5' is assumed to be shale with the remainder sandstone.

The excavation costs for shale and sandstone, assuming portal access and openings of 50', are \$8.80 and \$4.40/cu yd, respectively. For simplicity in the calculations, these figures can be converted to a cost per square foot for one and two level space. For 17' high space with 5' of shale and 12' of sandstone, the cost is \$3.69/ft^2. For 30' high space with 5' of shale and 25' of sandstone the cost is \$5.70/ft^2.

wall and floor systems

The exterior wall systems required for mined space reflect three different conditions. The first is a totally unfinished space with no water problems, using exposed sandstone walls treated with sodium silicate. Since exposed sandstone walls are limited to a few special uses, a more typical wall system for mined space with no water problems would be an 8" thick reinforced concrete wall which is the second alternative. The third condition is for space with groundwater problems. The wall system used includes a layer of gunite over the sandstone, a waterproof membrane and an 8" thick reinforced concrete wall on the interior. Typical costs for an 8" thick reinforced concrete wall are about \$5.75/ft^2 including labor, materials and finishing. This cost is reduced to \$4.75/ft^2 to reflect finishing on one side only and some economy in the use of steel forms on one side only. The costs are stated below:

ITEM	TYPE I	TYPE II	TYPE III
trimming & spraying sodium silicate	\$2.00/ft^2	\$2.00/ft^2	\$2.00/ft^2
2" gunite	2.25		
waterproof membrane	1.00		
8" reinforced concrete	4.75	4.75	
TOTAL	\$10.00/ft^2	\$6.75/ft^2	\$2.00/ft^2

The floor systems required for mined space are similar to the wall systems but do not include an alternative of exposed sandstone since any foreseeable use would require a minimal concrete floor. Thus, two alternatives are presented, a simple 6" concrete slab for no water problems and 8" reinforced concrete slab with a waterproof membrane over 2" of concrete for areas with some water.

ITEM	TYPE I	TYPE II
2" concrete	\$ .30/ft^2	
waterproof membrane	1.00	
8" reinforced concrete	2.30	
6" concrete (w.w. mesh)		\$1.65/ft^2
TOTAL	\$3.60/ft^2	\$1.65/ft^2

ceiling system

It is assumed that all mined space will require rock bolting into the limestone roof and a ceiling to protect the space from moisture from above. The type and cost of the ceiling could vary considerably. A simple, economic method of providing this drip cap is to hang corrugated fiberglass panels from the rock bolts supported by a system of metal struts. Fiberglass panels cost from $1.00 to $1.50/ft^2 for installation and materials in a normal roofing situation. The remainder of the $4.00/ft^2 indicated for a hung ceiling includes the hangers and struts as well as a simple gutter and drainage system along the edges of the ceiling.

ITEM	COST
rock bolts	$1.25/ft^2
hung ceiling system	4.00
TOTAL	$5.25/ft^2

internal structural system

In most mined space there is the possibility of creating two levels within the limits of available space. Of course, the specific designs and costs of even the basic floor structure can vary considerably. A typical concrete waffle slab system supported by columns costs approximately $5.00/ft^2 with 25' bays and $6.00/ft^2 with 30' bays assuming a 150 lb/ft^2 live load. However, it may be desirable to span the entire 50' bay of mined space and eliminate columns. The typical cost for pre-cast double T's for this span is about $4.00/ft^2. However, there would be difficulty in installation not found in typical construction. Therefore, if pre-cast T's are possible at all, a cost of $6.00/ft^2 may be more realistic. Another alternative is poured-in-place concrete beams spanning 50' with a concrete deck. This typical cost for such a system would be about $7.00/ft^2. For the examples and calculations presented in the following sections, a figure of $6.00/ft^2 for the internal structure is used. However, for any specific design this figure should be examined and adjusted to fit the conditions.

shafts and vertical circulation

▪ excavation and lining

An estimate of the cost of drilling or blasting various sizes of shaft was obtained from local drilling companies. These were compared and adjusted and the cost of providing other sizes of shafts estimated. Larger shafts (25'-30' in width) were made to fit in reasonable progression to a 50' x 50' deep cut building calculated from the data given in excavation costs. The costs given are for 110' deep shafts through 50' of overburden, 30' of limestone and 30' of sandstone. They include excavation and hauling, any temporary support and the final lining. A rough breakdown between the cost of the shaft in the different layers is also shown. Circular shafts have approximately 20% less cross sectional area than a square shaft and require less reinforcement in the lining and hence, their costs are reduced from those of a square shaft.

WIDTH OR DIAMETER	SQUARE SHAFTS	CIRCULAR SHAFTS
5 ft.		$ 39,000
10	$ 60,000	50,000
15	130,000	100,000
20	200,000	155,000
25	270,000	210,000
30	340,000	265,000

PERCENTAGE OF COST:
50' overburden: 35%
30' limestone: 50%
30' sandstone: 15%

▪ total shaft costs

Shafts are required in almost any mined space development for vertical circulation and the mechanical equipment. For purposes of estimating the costs of excavation and lining are combined with vertical circulation costs to give complete unit costs that can be used in feasibility studies. All of the shafts chosen are circular and contain some mechanical space in addition to the stairs and elevators that are indicated. The stairs are simple concrete fire stairs and the elevators are all 4,000 lb. capacity at 500 fpm except for the service elevator. The enclosure walls are 8" thick reinforced concrete and fully enclose the elevators or stairs. These costs are given for two conditions of mined space shown on the two charts below. In the first chart, all the shafts are assumed to be 110' in length and originate at the surface. In the second chart, the shafts are 60' in length and originate at the base of a 50' deep cut and cover building founded on the limestone. However in the second chart the cost of the elevators, stairs, and enclosure walls are for the entire 110' from the surface. Thus the vertical circulation in the second group of shafts serves four levels of cut and cover space as well as two levels of mined space.

mined space shaft costs (110 ft. from surface)

ITEM	15' DIAM. SHAFT		20' DIAM. SHAFT		25' DIAM. SHAFT	
	STAIRS	1 ELEV.	1 ELEV. & STAIRS	2 ELEV.	2 ELEV. & STAIRS	1 SERV. EL. & STAIRS
excavation & lining	$100,000	$100,000	$155,000	$155,000	$210,000	$210,000
elevators		98,600	98,600	196,200	196,200	58,900
stair construction	12,000		12,000		12,000	12,000
enclosure walls	13,200	18,000	30,000	21,600	52,800	49,200
TOTAL	$125,200	$216,600	$295,600	$372,800	$471,000	$330,100

mined space shaft costs (below 50 ft. deep cut space)

ITEM	15' DIAM. SHAFT		20' DIAM. SHAFT		25' DIAM. SHAFT	
	STAIRS	1 ELEV.	1 ELEV. & STAIRS	2 ELEV.	2 ELEV. & STAIRS	1 SERV. EL. & STAIRS
excavation & lining	$ 65,000	$ 65,000	$100,800	$100,800	$136,500	$136,500
elevators		112,700	112,700	225,400	225,400	71,000
stair construction	12,000		12,000		12,000	12,000
enclosure walls	20,300	20,200	36,600	-27,100	52,800	49,200
TOTAL	$ 97,300	$197,900	$262,100	$353,300	$426,700	$268,700

▪ diagonal shafts

For certain special uses such as transit requiring a continuous flow of large volumes of people to a mined space, high speed escalators are possibly the only solution. Although escalators to mined space are unlikely for most foreseeable functions in the University area, the costs are given here for comparison. The excavation is entirely different than a vertical shaft requiring retaining of a large open trench, construction of the shaft and backfilling over the shaft. The construction costs for a 20' x 20' shaft are given below along with the approximate cost of two 48" wide high speed escalators.

ITEM	UNIT COST	QUANTITY	COST
excav.: overburden	$ 3.00/c.y.	5,000 c.y.	$ 15,000
retaining	16.50/ft²	10,900 ft²	179,850
backfill	2.20/c.y.	3,500 c.y.	7,700
limestone	30.00/c.y.	910 c.y.	27,300
pre-splitting	4.40/ft²	4,660 ft²	20,505
rock bolts	1.25/ft²	5,260 ft²	6,575
sandstone	15.00/c.y.	890 c.y.	13,350
lining: overburden	8.00/ft²	8,000 ft²	64,000
limestone	10.00/ft²	4,800 ft²	48,000
sandstone	10.00/ft²	4,000 ft²	40,000
SUB-TOTAL			$422,280
escalators	$300,000	2	600,000
TOTAL			$1,022,280

portals

In typical mined space construction in the University area portal access from the river bluffs is a likely component of the design. For structural reasons the opening is usually limited to 30' in width and no larger mined space can be opened for the first 50' of the tunnel. Therefore, a typical 30' x 50' portal is used for estimating purposes. The special costs which are included in the portal opening are rock bolts into the face of the limestone on the bluff, and 12" thick concrete walls and roof around the opening extending 5' out from the limestone face and 10' back into the tunnel. These costs are presented below along with the standard costs used for excavation, floor and wall treatment, and ceiling systems for the portal.

ITEM	COST
rock bolt limestone face	$ 2250
concrete walls (17'x15'x12")	2700
concrete roof (15'x30'x12")	4050
TOTAL	$ 9000

excavation

▪ overburden

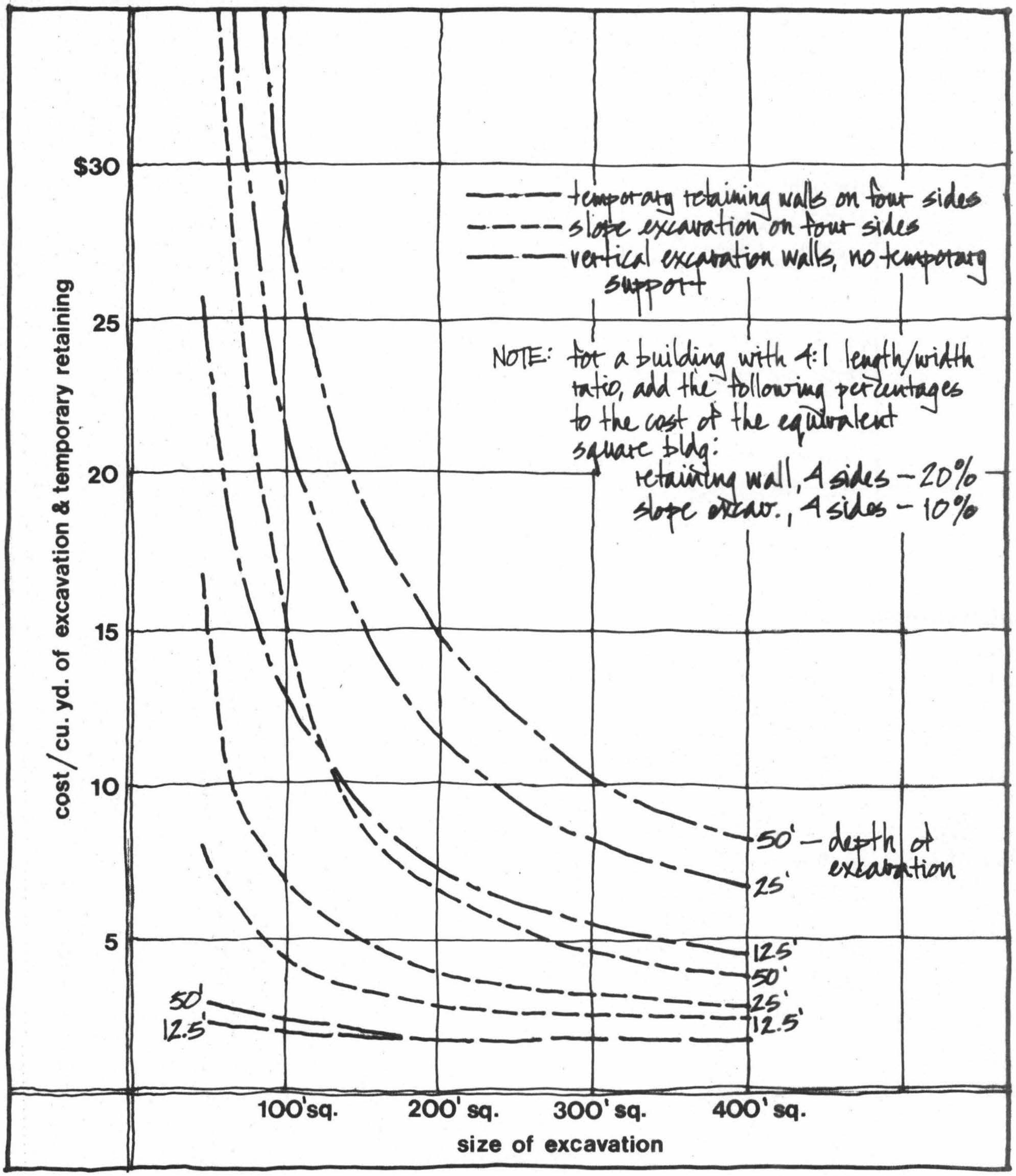
Excavations in the overburden have been priced using the following basic costs:

ITEM	UNIT COST	NOTES:
excavation:		These figures include a 5 mi. haul for disposal and allow for 50¢/cy resale value.
front end loader	$1.87/cu.yd	
dragline	2.09	
clamshell	3.63	
backfill-compaction	$2.20/cu.yd	
temporary retaining wall:		These figures include the cost of tie backs, wa lings, etc. and allow for extraction & recovery.
12.5' deep	$8.80/ft²	
25' deep	16.50	
50' deep	22.00	

The feasibility of ramping into various excavation sizes was examined and the volume of the ramp calculated for each case. Using this information, the proportions of each excavation that could be excavated by front end loader, dragline or clamshell were established and an average cost per cubic yard of excavation calculated. Nine curves for excavation and temporary retaining costs were worked up from these figures. In all cases the cost/cu yd of excavation is based on the final size of the building and, except for the no support case, allowance is made for an excavation 4' larger than the building all round and the subsequent backfilling. Slope costs are figured at a 1½ (horizontal) to 1 (vertical) slope and the cost of backfilling this slope included with it. The costs are figured for square excavations but an approximate percentage change in cost is shown for an excavation with a length : width ratio of 4:1. The costs are also based on all four sides of the excavation having the same treatment. Costs for excavations with different treatments can be estimated by interpolation between the appropriate cases shown.

As can be seen from the graph, the cost/cu yd of providing a retained excavation drops rapidly with increasing width of excavation. This is because the cost of temporary retaining dominates the total excavation cost. Where no retaining is required the cost drops only slightly as the excavation becomes wider. Slopes are much cheaper than a retaining wall except on small and deep excavations but they require a much larger site than the finished size of the building to be an alternative. The savings in excavation cost when abutting an existing deep building can be quite dramatic. For example: a 200' sq. building excavation 50' deep with all sides retained will cost approximately $14.80/cu yd. The same excavation with 1 side abutting a deep building will cost by interpolation $11.60/cu yd; with 2 sides abutting, $8.35 (savings of 22% and 44% respectively). For comparison with the other costs of a building, the costs per cu yd can be converted to a cost per sq. ft. of floor area (assuming a 12.5' floor/ceiling height) by dividing by 2.16. For the 200' sq. building 50' deep retained on all sides, the figure would be $6.85/ft².

cut and cover excavation costs in overburden



▪ rock

Excavations in limestone and sandstone in a cut and cover situation have been priced using the following basic costs:

ITEM	UNIT COST
limestone excavation:	
50' and 100' sq. bldgs.	$22.00/cu.yd
150' and 200' sq. bldgs.	16.50
300' sq. & larger bldgs.	11.00
presplitting for blasting	4.40/ft²
rock bolting walls	1.25/ft²
sandstone excavation:	
50' to 200' sq. bldgs.	$5.50/cu.yd.
300' sq. & larger bldgs	4.40

wall systems

For cost estimating purposes in this report, three exterior wall systems have been selected as typical for large projects which correspond to the three major geological layers. For all cut and cover space in the overburden, which is the first 50' in the campus area, it is assumed a temporary retaining wall will be used and the exterior walls will be 18" thick cast-in-place concrete with a high quality waterproof membrane applied to the outside surface. For any cut and cover space deeper than 50' and, therefore, cut into the limestone and sandstone, a slightly different system would be used. The wall would consist of a 2" layer of gunite applied to the bedrock, a waterproof membrane applied from the inside and then the 18" thick reinforced concrete wall formed from the inside. The only difference between the exterior wall costs in limestone and sandstone is an additional $\$2.00/ft^2$ in sandstone for trimming and spraying with sodium silicate as necessary. A typical cost for an 18" cast-in-place concrete wall is about $\$7.74/ft^2$ and this is used in the overburden walls. The cost used for the 18" wall in bedrock is $\$6.75/ft^2$ to reflect a reduction in finishing costs and economies in forming only one side of the wall with steel forms. If different methods of construction are likely to be used, these figures should be adjusted accordingly.

ITEM	OVERBURDEN	LIMESTONE	SANDSTONE
trimming sandstone and spraying silicate			$2.00/ft²
2" gunite		$2.25/ft²	2.25
waterproof membrane	$1.00/ft²	1.00	1.00
18" reinforced concrete	7.75	6.75	6.75
TOTAL	$8.75/ft²	$10.00 ft²	$12.00/ft²

floor systems

For the cost estimating purposes of this report, it is assumed that the floor slab of any cut and cover structure is designed to be waterproof. The two depths of cut and cover space which are used in illustrating costs are 50' with the floor slab on top of the limestone layer and 110' with the floor 30' deep into the sandstone. In both cases a waterproof membrane is placed over a 2" layer of concrete. In the 110' deep space in sandstone, an 8" reinforced concrete slab should be sufficient to withstand any water pressure assuming the perched water is mostly sealed around the building. In the 50' deep space there is potentially greater water pressure from the perched water table, so a 12" reinforced concrete slab is indicated.

ITEM	50' DEEP	110' DEEP
2" concrete	$ .30/ft²	$ .30/ft²
waterproof membrane	1.00	1.00
8" concrete slab		2.30
12" concrete slab	3.10	
TOTAL	$ 4.40/ft²	$ 3.60/ft²

structural system

In order to provide an estimate of the cost of unfinished cut and cover space, the internal structure must be included. Obviously, the structural system can vary considerably and any costs given here must be reviewed and adjusted to any specific conditions. For simplicity, cut and cover space of only two depths is considered. The first is 50' with four levels and the second is 110' with eight levels. In both cases the system used is a concrete waffle slab system supported by concrete columns spaced 30' apart with an assumed live load of 150 lbs/ft^2. The average cost of a system such as this is \$6.25/ft^2 for four levels and \$6.75/ft^2 for eight levels. These figures include a sufficient amount to cover any foundation costs for the columns, assuming they are founded on bedrock in both cases. The difference in the two figures reflects the increased column sizes required to support the additional levels in the deeper structure.

surface deck

In a cut and cover building, any above ground structures, sitework, open courts and surface treatment are an important part of the design and the costs. However, these costs vary widely and are not considered as part of the basic shell of the building. In order to estimate the cost of the basic unfinished building, a surface deck at ground level is included. The deck consists of a waterproof membrane and 5" of insulating lightweight concrete. Any finish or additional earth cover can be applied to this. This component can be adjusted or eliminated depending on the specific design being considered.

ITEM	COST
waterproof membrane	$ 1.20/ft^2
5" insulating conc.	1.10
TOTAL	$ 2.30/ft^2

vertical circulation

The costs presented in this section are used to determine the cost of unfinished space as well as to compare various types and configurations of space. In mined space, shafts and vertical circulation are an extremely important cost factor and must be included in these basic costs. Therefore in order to compare the two types of space properly, the cost of vertical circulation is included in cut and cover space as well. Since different sizes and types of buildings have vastly different vertical circulation requirements, only the simplest units are presented here and they can be placed in various combinations to quickly determine relative costs. Figures are given for 50' deep and 110' deep cut and cover space. The stairs referred to are typical concrete fire stairs and the elevators are 3,000 lb., 500 fpm passenger elevators. The costs of enclosure walls refer to 8" thick reinforced concrete walls surrounding the stair or elevator shaft. No escalators are included in cut and cover space calculations since the costs are only meaningful when applied to a specific design.

ITEM	50' DEEP			110' DEEP		
	STAIRS	1 ELEV.	2 ELEV.	STAIR	1 ELEV.	2 ELEV.
elevators		$103,300	$206,600		$122,100	$244,200
stair construction	$ 5,500			$ 12,000		
enclosure walls	13,100	10,400	15,300	28,800	22,800	33,600
TOTAL	$ 18,600	$ 113,700	$221,900	$ 40,800	$144,900	$277,800

remaining project costs

The previous basic costs for both mined and cut and cover space can be used to determine the approximate cost of the unfinished shell of space. These costs should apply to any use of the space. In order to compare underground space with other alternatives, the remaining costs of the total project must be included. These costs are presented here for various uses of the space.

mechanical-electrical systems

In general, the cost of mechanical and electrical systems in underground space should not be significantly different from costs in above ground space. The chart below gives approximate cost figures that can be used in feasibility studies. These costs are taken from 1975 Dodge Construction Systems Costs and represent only general averages. They are for typical above ground construction, so certain minor differences in underground space should be taken into account.

In mined space ventilation ducts in the shafts and sufficient air handling equipment to move the air through the additional 100 feet of shaft would be required for any outside air supply. These additional costs may be offset somewhat by the fact that connection to existing steam and sewer systems already located in mined space should be less costly since no shafts are required. In cut and cover space, the costs should not differ significantly from above ground construction.

	COLLEGE CLASSRM.	COLLEGE LAB	COLLEGE DINING	LIBRARY	OFFICE (LOW RISE)	WAREHSE.	PARKING GARAGE
hvac	$\$9.01/\text{ft}^2$	$\$14.83/\text{ft}^2$	$\$5.63/\text{ft}^2$	$\$8.45/\text{ft}^2$	$\$3.90/\text{ft}^2$	$\$2.35/\text{ft}^2$	$\$.39/\text{ft}^2$
plumbing	2.20	3.73	2.97	2.21	1.81	1.42	.55
electrical	7.65	5.15	3.94	7.11	2.91	1.98	1.33
TOTAL mech-el	18.86	23.71	12.54	17.77	8.62	5.75	2.27
TOTAL PROJECT	43.13	46.96	47.63	48.04	30.74	17.44	11.78

One possible use of underground space is parking and the mechanical costs indicated for above ground parking structures are clearly not applicable below ground. Although no great amount of heating or cooling is required, a substantial ventilation rate is necessary. There are very few available costs on this type of mechanical system. One study suggests that such a system would cost roughly $800 to $1,000 per car. This is quite costly--although this may be reduced if the system does not have to be designed for the situation when all cars are running simultaneously. It is important that this substantial additional cost is included in any feasibility studies for parking.

A final consideration in determining mechanical costs for underground construction and mined space in particular, concerns the relocation of existing utilities. Costs of relocation are difficult to present in a general study such as this due to the great variety of conditions which can occur. It is possible that a major sanitary sewer may act as a barrier to development because the cost of relocation is so great. However, it is also possible that a steam tunnel or storm sewer can easily be incorporated into mined space development. Generally, for a very small development, utility relocation costs would be a substantial part of the total cost, but for development of any size utility and relocation would not represent a great cost factor. None of the comparisons or examples in the following sections include utility relocation in the costs, although in most cases the examples are located to avoid major utility concentrations.

finishing and misc. costs

In most cases the costs of partition walls, finishing and various miscellaneous costs in the interior of underground space should be similar to costs in above ground space. Since finishing costs can vary a great deal depending on the design and quality of the space, specific cost figures are not too meaningful. Nevertheless, for purposes of comparison and to give a complete picture of total costs, some average finishing costs are given here, taken from 1975 Dodge Construction Systems Costs. Obviously, if more reliable data on these costs is available, it can easily be substituted in any feasibility studies.

	COLLEGE CLASSRM.	COLLEGE LAB	COLLEGE DINING	LIBRARY	OFFICE (LOW RISE)	WAREHSE.	PARKING GARAGE
partitions	$ 2.81/ft²	$ 2.95/ft²	$ 2.65/ft²	$ 1.92/ft²	$ 3.17/ft²	$ .55/ft²	$ .09/ft²
wall finishes	.43	.39	1.04	.85	.40	.26	.07
floor finishes	.48	.40	1.35	.28	.59	.22	.12
ceiling finishes	.72	.24	.81	.59	.81	.24	.10
specialties	.93	.58	2.40	.26	.50	.52	.05
fixed equipment		.09	9.76	.66	.31	.43	.06
general cond.	1.89	2.51	2.72	3.44	1.55	.93	.62
SUB-TOTAL	7.26	7.16	20.73	8.00	7.33	3.15	1.11
TOTAL PROJECT	43.13	46.96	41.63	48.04	30.74	17.44	11.78

surface structures and site work

A final segment of underground construction which must not be overlooked in any approximation of total costs is the required surface structures and site work. This is another area in which general cost estimates are almost meaningless due to the wide variety of possible conditions and designs. Once a specific design is assumed, however, cost data on conventional structures and site work is available and should be quite applicable.

In mined space there are two areas requiring possible site work and structures. The first is the portal area along the river bluffs and due to the relatively small scale of the portal and immediate area, substantial costs should not be incurred here. The second is the surface area where any shafts emerge. If the vertical circulation to mined space emerges within existing surface or cut and cover buildings, virtually no site work is attributable to mined space. However, in some cases, entire structures may be built only to serve as an entrance to mined space. In the case of transit stations, preliminary estimates include $30,000 to $40,000 for small structures which house the escalators at the surface. Obviously, the amount and cost of site work can vary greatly for these surface entry areas. However, for most developments they represent a small part of the total cost, probably far less than the site work for a typical building of comparable size.

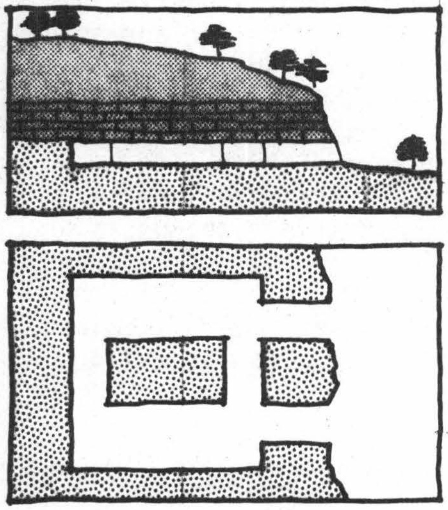
For cut and cover space, the site work may represent a much greater portion of the total cost. Most cut and cover space would include entrance structures above ground or sunken courts. Again, average costs are not applicable without a specific design in mind. However, it is likely that any good quality surface treatment would at least equal the cost of site work for a comparable above ground structure and may be somewhat greater. Nevertheless, additional site-work and surface treatment for underground space would be offset by the lack of exterior treatment required on the building itself. In the following comparisons partial figures for site work or surface structures are included, but they must be examined and revised for any realistic reflection of total costs.

In the design of underground space there are obviously many factors which influence the total cost. It is beyond the scope of this report to explore detailed design alternatives and present specific cost factors. However, it is useful to examine some very basic design relationships that do have quite important cost implications. By using the basic costs from the previous section, estimates for various designs and layouts can be easily made and the cost per square foot of the alternatives compared. In order to clearly compare various layouts, all of the estimates in this section are for unfinished space. To arrive at a total cost, the mechanical-electrical, finishing and any site work costs must be included. Since the cost of the unfinished shell remains about the same for any function, the total cost of various uses can be estimated by applying the appropriate finishing and mechanical cost for a given function. In the comparisons which follow for mined space, the relative costs of one and two level space are compared as well as the effect of shaft and portal access on construction costs and layout. For cut and cover space, structures of various sizes and depths are used to illustrate certain cost relationships. Also, costs for mined space connected to cut and cover space are presented.

mined space: height of space

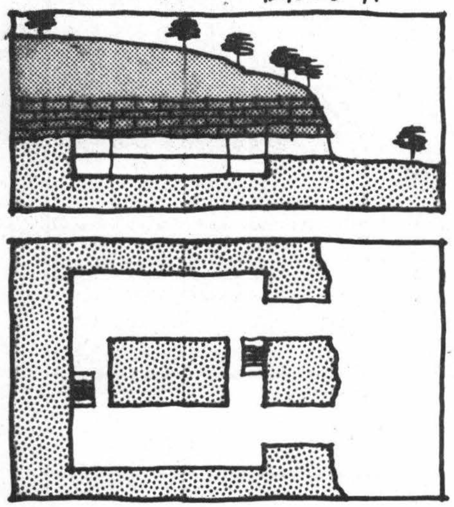
Within the campus area, it is assumed that the height of mined space is limited to a 30'-40' layer beneath the limestone and above the main water table. Preliminary design studies indicate that one level of mined space beneath the limestone requires a 17' high excavation since a maintenance and mechanical space is required above the standard usable space. A two level space would then require about a 30' high excavation so it appears that two levels is the likely limit for mined space development. The major difference between one and two level space is the internal structural system required to support the upper floor level in two level space. The fact that a standard reinforced concrete structural system is at least as costly as additional excavation would make it appear that one level space may be more economical than two. However, the figures below indicate that the case is just the opposite. The average cost per square foot for two level space is less than that of one level space. This is due partly to the fact that the 17' excavation for one level space which includes 5' of shale is really more costly than the excavation of an additional 13' of sandstone for the second level. Also, the cost of the rock bolts in the limestone and the waterproof hung ceiling necessary in mined space total $\$5.25/ft^2$ which is a substantial cost not found on the second level. Therefore, the cost of excavation and the internal structure for the second level of space is less than the excavation and ceiling structure of an equivalent amount of single level space. This is true even for an internal structural system somewhat more expensive than the one indicated in these calculations. There are other factors that do not enter into these calculations which also contribute to the economic advantages of two level space. Shafts from the surface with vertical circulation and mechanical ducts can more efficiently serve two levels which should represent some reduction in shaft costs. Also, the layout of space in two levels is much more concentrated, allowing for more efficient pedestrian circulation and mechanical layout within the development.

one level space: 21,000 ft²



ITEM	QUANTITY	TYPE I	TYPE II
excavation	21,000 ft²	$ 75,390	$ 75,390
walls	17,340	173,400	117,045
floors	21,000	75,600	34,650
ceiling	21,000	110,250	110,250
internal structure	-		
portal structure	2	14,000	14,000
stairs			
TOTAL		$448,640	$351,335
COST/FT²		$21.36	$16.73

two level space: 42,000 ft²

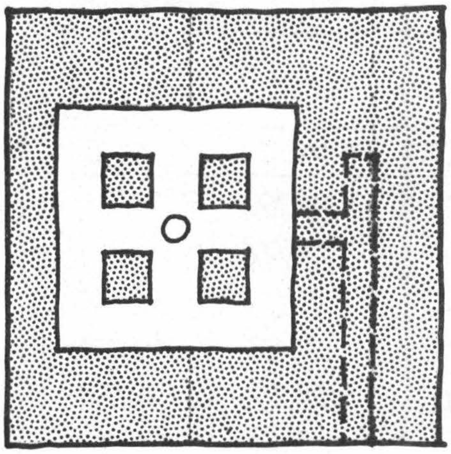


ITEM	QUANTITY	TYPE I	TYPE II
excavation	21,000 ft²	$ 119,700	$ 119,700
walls	30,600	306,000	206,550
floors	21,000	75,600	34,650
ceiling	21,000	110,250	110,250
internal structure	20,700	124,200	124,200
portal structure	2	14,000	14,000
stairs	2	16,000	16,000
TOTAL		$765,750	$625,350
COST/FT²		$18.23	$14.89

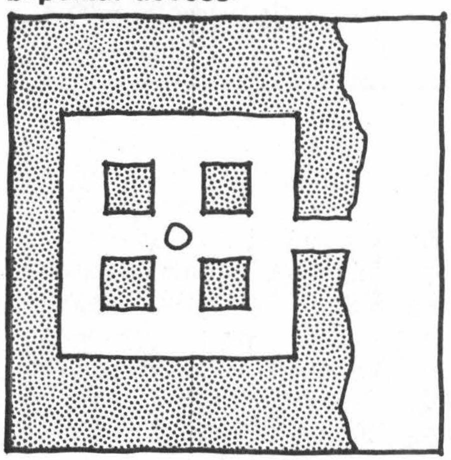
mined space: portal and shaft excavation costs

In the excavation costs presented earlier, it was noted that the costs are affected considerably by the type of access available for construction equipment. Assuming an excavation of reasonable size, the costs are lowest for mined space with portal access from the river bluffs where trucks and other large equipment can enter the space through a tunnel. The other type of access for construction is through a shaft where small equipment can be lowered. The cost with shaft access is estimated to be twice as high as portal access for sandstone and 50% higher for shale. This reflects the multiple handling and therefore greater labor costs in excavation. These cost differences indicate that perhaps for some mined space away from the river bluffs it may be more economical to drive an access tunnel to the space than to mine it from a shaft. The following example illustrates this possibility. A typical mined space development of 108,000 ft^2 was selected and the excavation costs were determined for both portal and shaft access. Then the cost per lineal foot of a 30' wide access tunnel is calculated. By using these rough figures, the length of an access tunnel from the river bluffs which is equal to the difference between shaft and portal excavation costs can be determined. In the example given, an access tunnel 823' in length is equal in cost to the added excavation costs through a shaft. This means that it is more economical to drive a tunnel from the bluffs for any space up to 823' from the portal entrance than it is to mine it from a shaft. For a mined space development twice as large as the one in the example, a tunnel twice as long would be justified. This is a purely hypothetical situation and actual development would probably not begin with a long tunnel to a distant site. Instead, as development grows away from the immediate bluff area, very small additions to an existing access tunnel will result in substantial savings in excavation costs. These figures do not include the fact that other costs such as concrete work may be increased when no direct truck access is available which makes the savings even greater. The extension of a tunnel system to most mined space may have additional benefits such as providing service access as well.

a: shaft access:



b: portal access:



excavation cost comparison

ITEM	UNIT COST	QUANTITY	COST
a: shale	$13.20/cy		
sandstone	8.80/cy		
30' high space	10.60/ft²		
excavation	10.60/ft²	54,000 ft²	$572,400
b: shale	8.80/cy		
sandstone	4.40/cy		
30' high space	5.70/ft²		
excavation	5.70/ft²	54,000 ft²	$307,800
COST DIFFERENCE:			$264,600

access tunnel costs

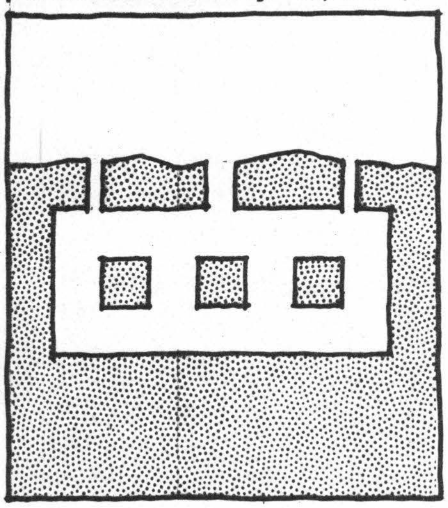
ITEM	UNIT COST	
excavation	$134.40/ft	
rock bolts	37.50	
6" conc. floor	49.50	
10' shaft @ 500' O.C.	100.00	
TOTAL	$321.40/ft	
LENGTH OF TUNNEL EQUAL TO COST DIFFERENCE		$\frac{\$264,000}{\$321.40/\text{ft}} = 823.3$ ft.

mined space: effect of shafts on layout and costs

One aspect of mined space planning which has a great impact on costs is the use and placement of shafts. In almost any mined space development away from the river bluffs shafts are necessary for access, emergency escape and mechanical equipment. The cost of these shafts is relatively high and careful attention must be paid to their efficient location and use. Without reference to a specific program and site, most generalized comparisons of shaft layouts have limited value. However, one simple comparison may serve to illustrate the effect they have on total costs. In the examples which follow, the cost of unfinished mined space is calculated for two different layouts of the same amount of space. One layout runs along the river bluff so that access can occur through a series of portals and no shafts are required. The second layout runs into the river bluff with a single portal access so that a second point of access is required through a shaft.

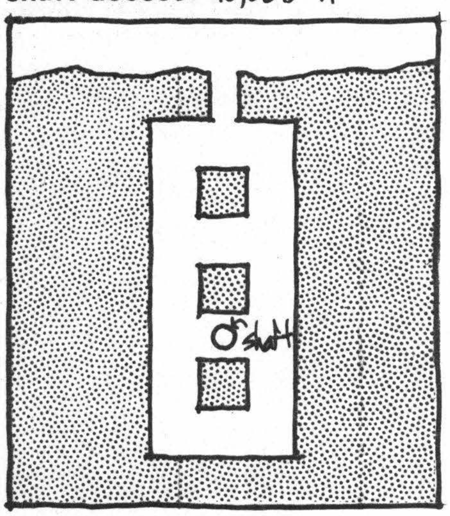
In the example, the shaft is assumed to be a 20' diameter circular shaft housing one elevator and an emergency staircase. Just the addition of the single shaft raises the cost of the unfinished space by 15 to 20% or almost \$3.00/ft^2 for this amount of space. As in the other examples, the figures for unfinished space must be added to the mechanical-electrical, finishing and sitework costs to arrive at an approximate total project cost. These figures are not directly applicable to other situations but they do serve to illustrate the relative importance of shaft layout in controlling costs. Since only the river bluff area can provide mined space with reduced shaft requirements, planning of river bluff sites should not overlook this cost advantage.

portal access only: 90,000 ft^2



ITEM	QUANTITY	TYPE I	TYPE II
excavation	45,000 ft^2	\$256,500	\$256,500
walls	45,300	453,000	305,775
floors	45,000	162,000	74,250
ceiling	45,000	236,250	236,250
internal structure	45,000	270,000	270,000
portal const.	3	114,225	92,190
shaft			
TOTAL		\$1,491,975	\$1,234,965
COST/FT^2		\$16.58	\$13.72

shaft access: 90,000 ft^2



ITEM	QUANTITY	TYPE I	TYPE II
excavation	45,000 sf	\$256,500	\$256,500
walls	47,100	471,000	317,925
floors	45,000	162,000	74,250
ceiling	45,000	236,250	236,250
internal structure	45,000	270,000	270,000
portal const.	1-30'	38,075	30,730
shaft	1-20'	295,600	295,600
TOTAL		\$1,729,425	\$1,481,255
COST/FT^2		\$19.22	\$16.46

cut and cover space: size and depth of structure

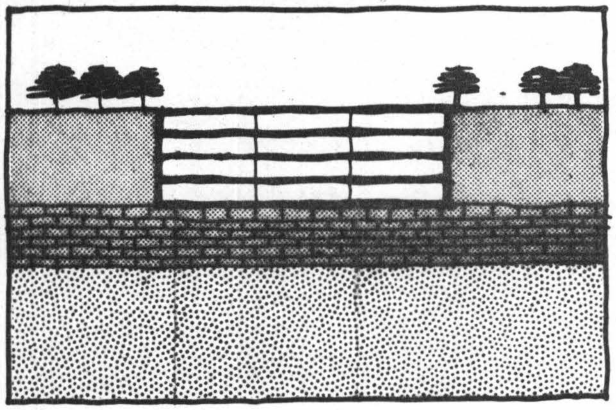
In any reasonably large size development of cut and cover space, it is important to understand how costs are affected by the size and depth of the structure. The cost of unfinished cut and cover space based on the figures given in the previous section is calculated here for four different examples. The first two examples are for structures 150' x 150', which approaches the minimum likely size for a deep building on campus. The first example is 50' deep or 4 levels and is excavated entirely in the overburden, while the second is 110' deep or 8 levels and requires excavation of 30' of sandstone, 30' of limestone, as well as the 50' of overburden. For purposes of demonstrating very simple relationships these two depths should be adequate. They also represent the most likely depths at which deep space would be developed. In the second two examples, structures 250' x 250' are used for the same two depths of 50' and 110'. This size excavation is quite large compared to most campus development and should serve to demonstrate any cost differences related to the size of development.

In all of the examples shown here and in the following section the costs are for unfinished cut and cover space. In order to fairly compare the figures with unfinished mined space, the cost of vertical circulation is included in both types of space since it is such an important factor in mined space especially. The amount of required vertical circulation depends on the use and occupancy level of the space. The figures selected in these estimates represent minimum amounts and any high occupancy use such as classrooms would have greater requirements. Other very simple aspects of design such as open courts or surface structures have been ignored in these calculations in order to focus on certain specific variables. Any attempt to estimate total project costs must take these factors into account.

▪ depth

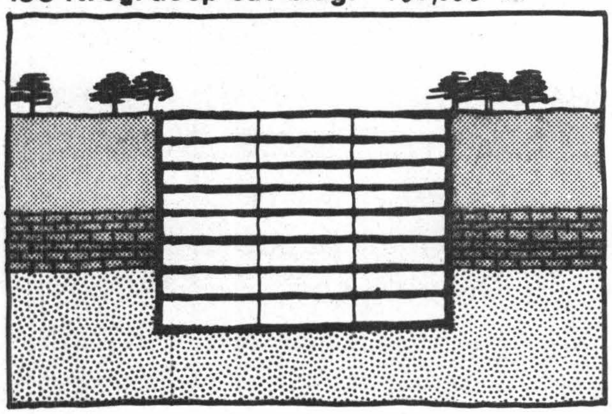
The calculations for both sizes of excavation indicate that deep space at 110' is approximately the same cost per square foot as the more shallow space at 50'. Most of the costs such as the internal floor structure and the permanent retaining walls remain about the same for any depth. The surprising fact is that the excavation costs remain similar for the overburden and the bedrock. Two main factors contribute to this. One is that the temporary retaining walls required for the overburden are by far the most costly part of excavating in the soil, whereas no temporary retaining is required in the bedrock. In the examples, it is assumed all four sides of the excavations are retained. If this were not necessary due to an adjacent building founded on bedrock, the costs of overburden excavation would drop considerably. The second factor is that by excavating equal amounts of limestone and sandstone, the rather high cost of limestone excavation is offset by the far lower cost of excavating sandstone. Limestone costs at least three times as much to excavate as sandstone, so an 80' deep building that required limestone excavation only in addition to the overburden would have a higher cost per square foot.

150 ft. sq. shallow cut bldg. 90,000 ft²



ITEM	QUANTITY	COST
excavation		$ 791,690
exterior walls	30,000 ft²	262,500
floor on grade	22,500	99,000
interior structure	90,000	562,500
surface cover	22,500	51,750
vert. circ: elev.	1	113,700
stairs	2	37,200
TOTAL		$1,918,340
COST/FT²		$21.31

150 ft. sq. deep cut bldg. 180,000 ft²

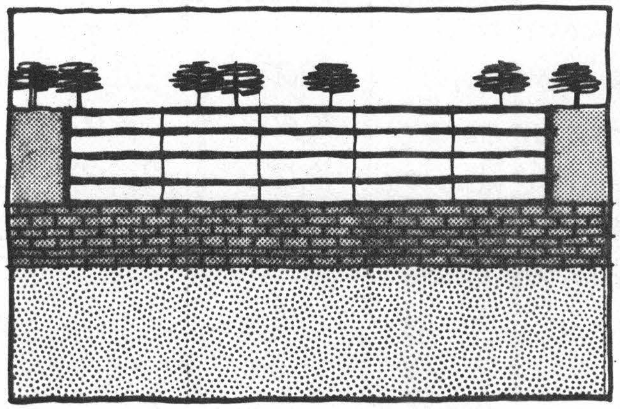


ITEM	QUANTITY	COST
excavation		$1,443,390
walls: overburden	30,000 ft²	262,500
limestone	18,000	180,000
sandstone	18,000	216,000
floor on grade	22,500	81,000
interior structure	180,000	1,215,000
surface cover	22,500	51,750
vert. circ: elev.	2	277,800
stairs.	2	81,600
TOTAL		$3,809,040
COST/FT²		$21.16

■ **size**

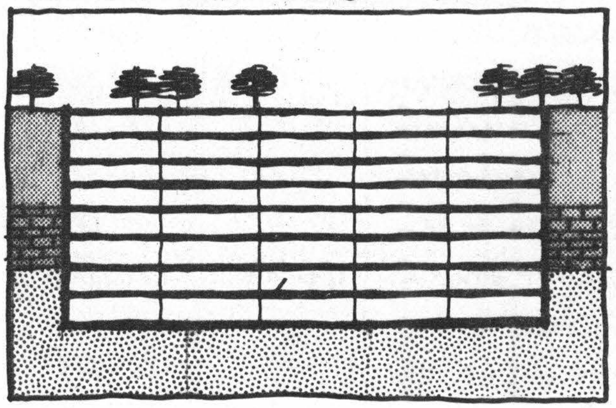
In examining the costs with respect to the two sizes selected in the examples, it appears that there is a significant reduction in the cost per square foot for the larger excavation. Since the costs are approximately the same for the two depths shown, the size is clearly the controlling variable. The reason for this is simply that as the perimeter walls increase in size, the area of usable floor space increases geometrically in relation to them. Since the greatest costs in unfinished deep cut and cover space are in the temporary and permanent retaining walls, the cost per square foot of floor area drops as the project size increases. Therefore, the 250' x 250' building, with 250,000 total square feet on four levels is almost the same cost as the 150' x 150' building with only 180,000 total square feet on eight levels. This is a considerable cost difference.

250 ft. sq. shallow cut bldg. 250,000 ft²



ITEM	QUANTITY	COST
excavation		$1,382,280
exterior walls	50,000 ft²	437,500
floor on grade	62,500	275,000
interior structure	250,000	1,562,500
surface cover	62,500	143,750
vert. circ: elev.	2	221,900
stairs	4	74,400
TOTAL		$4,097,330
COST/FT²		$16.39

250 ft. sq. deep cut bldg. 500,000 ft²

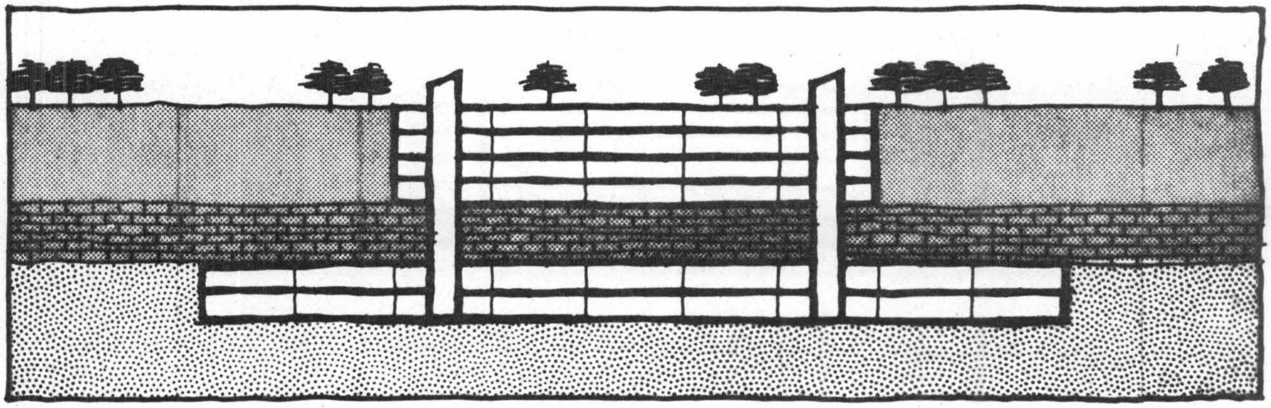


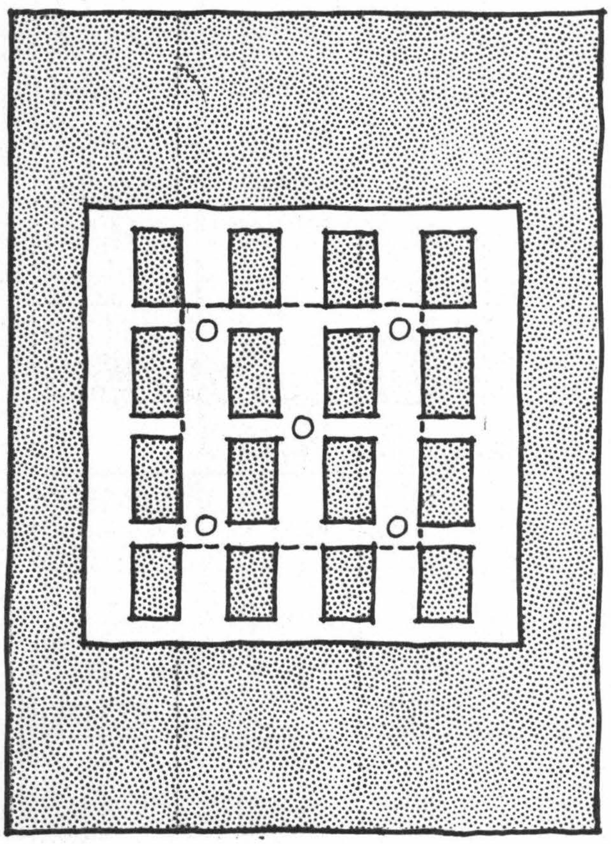
ITEM	QUANTITY	COST
excavation		$2,621,310
walls: overburden	50,000 ft²	437,500
limestone	30,000	300,000
sandstone	30,000	360,000
floor on grade	62,500	225,000
interior structure	500,000	3,375,000
surface cover	62,500	143,750
vert. circ: elev.	4	555,600
stairs	4	163,200
TOTAL		$8,181,360
COST/FT²		$16.36

cut & cover and mined space combined

One of the unique aspects of underground construction is the ability to connect cut and cover space to mined space. This can be done in two basic ways. The first is through shafts which connect 50' deep cut space to mined space below, and the second is by entering mined space directly from 110' deep cut space. One of the principle advantages of connecting the two spaces is that vertical circulation costs to mined space can be reduced because the shafts are shorter or not required at all and the elevators and stairs can more efficiently serve several levels. In the following examples, costs for unfinished space are calculated for both mined space below cut and cover space and mined space adjacent to it. A 250' x 250' cut and cover structure is used in both cases. The size of the mined space is determined by the maximum distance allowable from the emergency exits in the corners of the cut building without requiring additional

mined space below cut and cover space





mined space : 245,000 ft²

ITEM	QUANTITY	COST
excavation	122,500 ft²	$ 698,250
exterior walls	186,000	1,860,000
floor on grade	122,500	441,000
ceiling	122,500	643,125
internal structure	122,500	735,000
shafts: 15' stair	4	389,200
20' elev.	1	353,200
TOTAL		$5,119,775
COST/FT²		$20.90

cut and cover space : 250,000 ft²

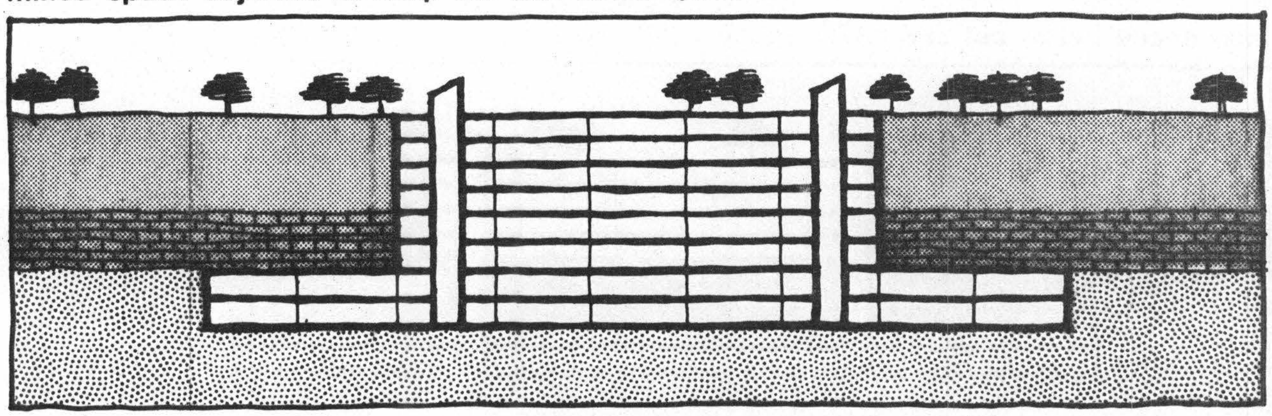
TOTAL	$4,097,330
COST/FT²	$16.39

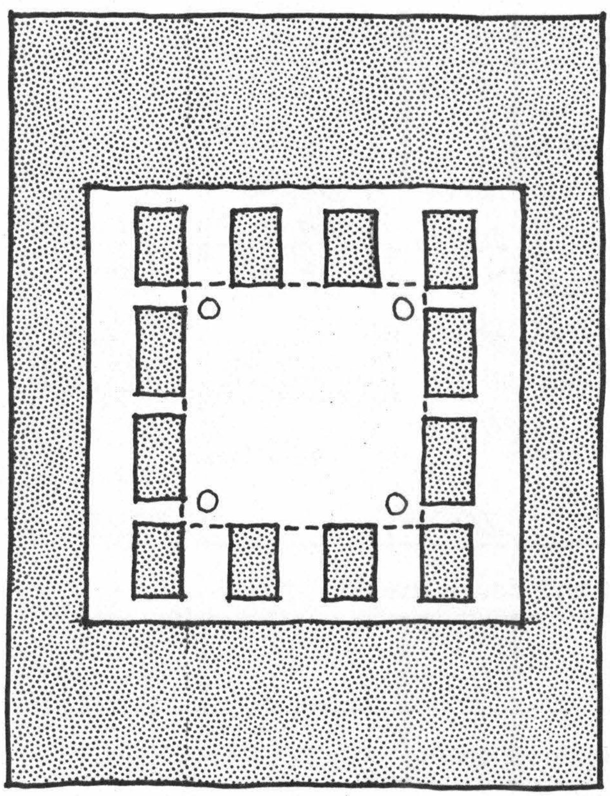
combined costs : 495,000 ft²

TOTAL	$9,217,105
COST/FT²	$18.62

shafts. In both cases additional elevators and stairs are provided to serve the additional space. However, the vertical circulation in these examples represent minimum requirements. The calculations indicate that mined space adjacent to deep cut and cover space is slightly less expensive than mined space below cut and cover. This is due to the extra costs of excavating and lining vertical shafts through the limestone which is not necessary in the deeper cut alternative. It is assumed that the mined space construction can be approached through an access tunnel and the excavation costs are based on this. It must be stated, as in all other examples, that mechanical-electrical, finishing, sitework, and any special design features are not included in the costs given here. These examples mainly serve to illustrate the possibilities of underground space and indicate that costs do not appear prohibitive for any of the alternatives shown.

mined space adjacent to deep cut and cover space





mined space : 178,000 ft²

ITEM	QUANTITY	COST
excavation	89,000 ft²	$ 507,300
exterior walls	133,800	1,338,000
floor on grade	89,000	320,400
ceiling	89,000	461,250
internal structure	89,000	534,000
vert. circ: elev.	2	277,800
TOTAL		$3,444,750
COST/FT²		$1924

cut and cover space : 500,000 ft²

TOTAL	$8,181,360
COST/FT²	$16.36

combined costs : 678,000 ft²

TOTAL	$11,626,110
COST/FT²	$17.12

analysis of total costs

The total cost of providing a functioning building is not reflected in the construction project cost alone. This is of course a major factor but must be considered along with land costs, maintenance costs and the cost of heating, cooling and providing the building with the necessary services for its function. This was discussed in general in the earlier report and in this section the factors will be listed and assigned with costs where possible. The savings for the underground space are compared with a total project cost developed in the next section. The comparison is made for mined space but would mostly apply to cut and cover space as well.

▪ land cost

In the range of $3.50-$6.00/ft^2 of the necessary land for above ground construction.

▪ property tax

No savings to the University from reduced land requirements since it does not pay such taxes. The surrounding community, however, does suffer a loss in tax base when extra land is required for above ground construction.

▪ insurance

No value assigned since the University acts as its own insurer. The reduced likelihood of extensive damage from fires, storms or explosion does, however, represent an indirect savings in underground construction.

▪ maintenance

No value assigned in this report but the savings in outside painting, cleaning, snow clearing and repairing storm and vandalism damage should be considerable.

▪ circulation

No value assigned in this report but the savings in University personnel's time could be assessed when a specific mined space location and function is compared with an alternative above ground site on the periphery of the campus.

▪ energy savings

Based on no internal heat gain from lights and people and a low ventilation load the savings in only 5 months of the heating season should be at least $0.06/ft^2/yr using a present cost figure of $3.00 per million BTU. The savings in the cooling season are not as easy to estimate but a minimum cost saving for the entire year should be around $0.10/ft^2/yr. Using the assumption of a permissible 33:1 original/annual cost ratio for public buildings, this would be the equivalent of a savings of $3.30/ft^2 in the original building cost.

The University's steam heating costs are reported as $1.115 per million BTU. NSP's consumer cost to its downtown St. Paul customers would be approximatly $3.16 per million BTU for very large quantities. IDS properties quoted a similarly higher figure. The commercial figures will represent the cost of steam including depreciation of equipment, other overheads and profit, whereas the University figure must represent only the incremental costs of providing steam. A figure of $3.00 is used in this analysis.

If a surface building were 4 stories high and covered 50% of the site area, the savings in land cost would be $2.00-3.00/ft^2 and the energy savings the equivalent of approximately $\$3.30/ft^2$. Thus, about $\$5.80/ft^2$ could be discounted from the initial cost of the underground building without including the other factors mentioned.

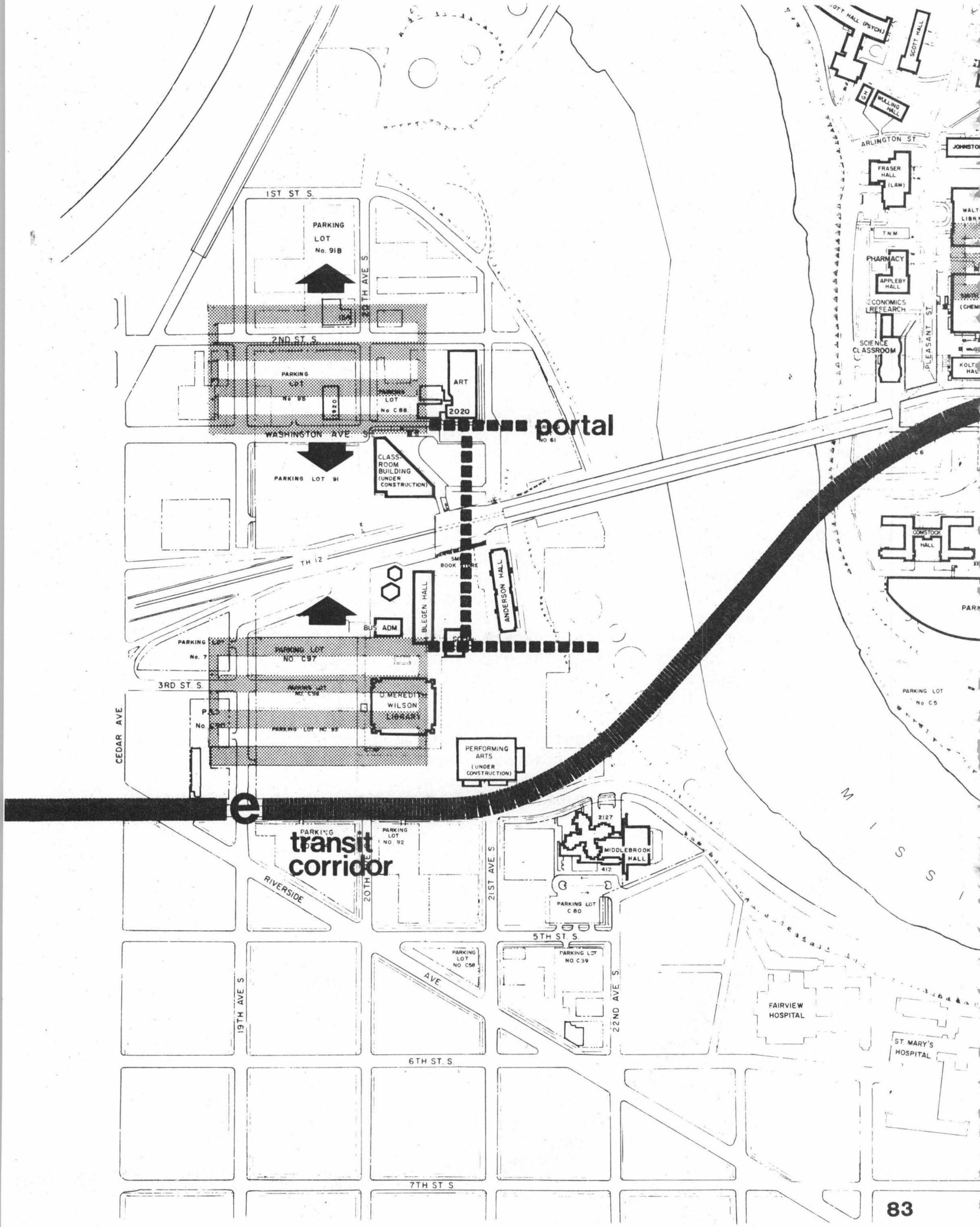
For laboratory space in dry sandstone, for example, the mined space cost could be effectively reduced from $\$54.51/ft^2$ to $\$48.71/ft^2$. The average cost of college laboratory space above ground is given in the Dodge Construction Systems Costs Manual as $\$46.96/ft^2$.

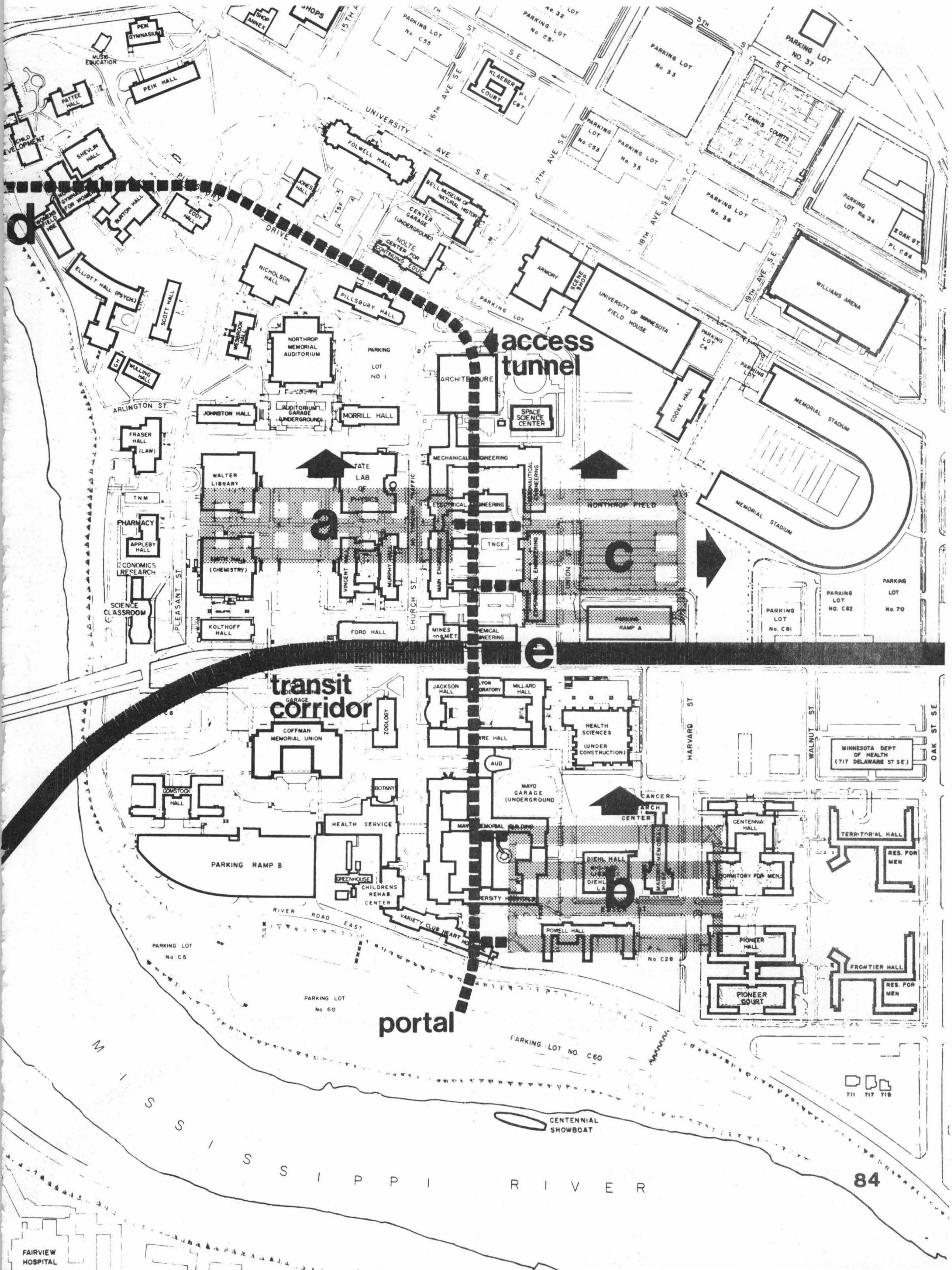
6 illustrative projects

introduction

In this section some possible projects on the Minneapolis campus with preliminary cost estimates are presented. Most of the examples are in mined space since cost data is less accessible and the design characteristics of mined space are less well known than those of cut and cover space. One purpose of this section is to demonstrate the cost estimating procedure used in this report by providing preliminary costs of these projects. The cost figures are presented in two parts for each design. The first part consists of the costs for the unfinished shell of space which is the same for most functions. The second part includes the remaining costs which consist of general averages for mechanical-electrical, finishing and sitework which apply to a specific function. This second part can be changed for different uses and new conditions or information. Then the two cost areas are combined to give a total construction cost figure for the design shown. In all of the cost figures, Type I space refers to fully waterproof, concrete lined space; Type II space refers to concrete lined space suitable for typical dry ground conditions; and Type III space refers to space with exposed sandstone walls. When only one cost is given, it is assumed to be for Type I space. It must be re-emphasized that detailed cost studies are beyond the scope of this report and any cost figures presented here are quite preliminary.

A second purpose of these hypothetical projects is to illustrate various layout and site areas for mined space on the campus which suggest major planning considerations. Although a definite plan of underground space use is not appropriate at this time, it is useful to develop an understanding of the amount and type of space available as presented in the examples in this section. Preceeding the actual projects are two maps which indicate the location of the projects and the major planning assumptions on which the examples are based. The most dominant features of mined space planning are the potential mass transit corridor in deep space as suggested by the MTC, and the available points of portal access along the river bluffs which suggest possible access tunnel locations. The transit corridor and access tunnels are indicated on the campus maps to illustrate their importance, but not necessarily to fix their location. The systems of mined space suggested on the maps and in the examples which follow are not intended to be a comprehensive presentation of sites and functions but simply a variety of possible projects which explore some likely sites and uses.


portal
transit corridor
1ST ST S.
PARKING LOT No. 91B
2ND ST S.
PARKING LOT No 95
ART
2020
PARKING LOT No C 88
WASHINGTON AVE. S.
PARKING LOT 91
CLASS-ROOM BUILDING (UNDER CONSTRUCTION)
TH 12
BOOK STORE
ANDERSON HALL
BLEGEN HALL
ADM
BUS
PARKING LOT No. 7
PARKING LOT NO. C97
3RD ST. S.
WILSON LIBRARY
CEDAR AVE.
PERFORMING ARTS (UNDER CONSTRUCTION)
PARKING LOT NO. 92
20TH AVE S
21ST AVE S
RIVERSIDE
2127
MIDDLEBROOK HALL
412
PARKING LOT C 80
5TH ST S
PARKING LOT NO. C58
PARKING LOT NO. C39
AVE
19TH AVE S
22ND AVE S
6TH ST. S.
7TH ST S
FAIRVIEW HOSPITAL
ST MARY'S HOSPITAL
PARKING LOT No C5
COMSTOCK HALL
C6
PARK
SCOTT HALL
WULLING HALL
ARLINGTON ST
JOHNSTON
FRASER HALL (LAW)
TNM
PHARMACY
APPLEBY HALL
ECONOMICS RESEARCH
SCIENCE CLASSROOM
PLEASANT ST
M
I
S
S


access tunnel
transit corridor
portal
a
b
c
d
e
PEIK GYMNASIUM
PEIK HALL
PATTEE HALL
SHEVLIN HALL
UNIVERSITY AVE S.E.
FOLWELL HALL
JONES HALL
EDDY HALL
BURTON HALL
BELL MUSEUM OF NATURAL HISTORY
NICHOLSON HALL
PILLSBURY HALL
ELLIOTT HALL (PSYCH)
SCOTT HALL
WESBROOK HALL
WULLING HALL
NORTHROP MEMORIAL AUDITORIUM
PARKING LOT NO 1
ARCHITECTURE
ARMORY
UNIVERSITY OF MINNESOTA FIELD HOUSE
WILLIAMS ARENA
COOKE HALL
MEMORIAL STADIUM
TENNIS COURTS
ARLINGTON ST.
JOHNSTON HALL
AUDITORIUM GARAGE (UNDERGROUND)
MORRILL HALL
SPACE SCIENCE CENTER
FRASER HALL (LAW)
WALTER LIBRARY
TATE LAB OF PHYSICS
MECHANICAL ENGINEERING
ELECTRICAL ENGINEERING
NORTHROP FIELD
TNCE
PHARMACY
APPLEBY HALL
ECONOMICS RESEARCH
SMITH HALL (CHEMISTRY)
VINCENT
MURPHY HALL
CHURCH ST.
MAIN ENGINEERING
SCIENCE CLASSROOM
PLEASANT ST
KOLTHOFF HALL
FORD HALL
RAMP A
PARKING LOT No. C81
PARKING LOT NO. C82
PARKING LOT No. 70
JACKSON HALL
MILLARD HALL
ZOOLOGY
COFFMAN MEMORIAL UNION
HEALTH SCIENCES (UNDER CONSTRUCTION)
HARVARD ST
WALNUT ST
OAK ST. SE
MINNESOTA DEPT OF HEALTH (717 DELAWARE ST SE)
MAYO GARAGE (UNDERGROUND)
BOTANY
COMSTOCK HALL
HEALTH SERVICE
PARKING RAMP B
GREENHOUSE
CHILDRENS REHAB CENTER
DIEHL HALL
CENTENNIAL HALL
DORMITORY FOR MEN
TERRITORIAL HALL
RES. FOR MEN
POWELL HALL
PIONEER HALL
PIONEER COURT
FRONTIER HALL
RIVER ROAD EAST
PARKING LOT No C5
PARKING LOT No 60
PARKING LOT NO C60
CENTENNIAL SHOWBOAT
MISSISSIPPI RIVER
FAIRVIEW HOSPITAL

a: archives/storage space

This project illustrates the costs and layout of 185,000 ft^2 of mined space on two levels located under the mall. The plan layout is the room and pillar system and it is assumed that an access tunnel is extended from the river bluffs. This space is designated as archives/storage space; however, the same costs for the unfinished space would apply to almost any function. For example, the same layout used for laboratory space would cost twice as much to construct but all of the additional costs would be in additional mechanical and finishing costs.

basic costs

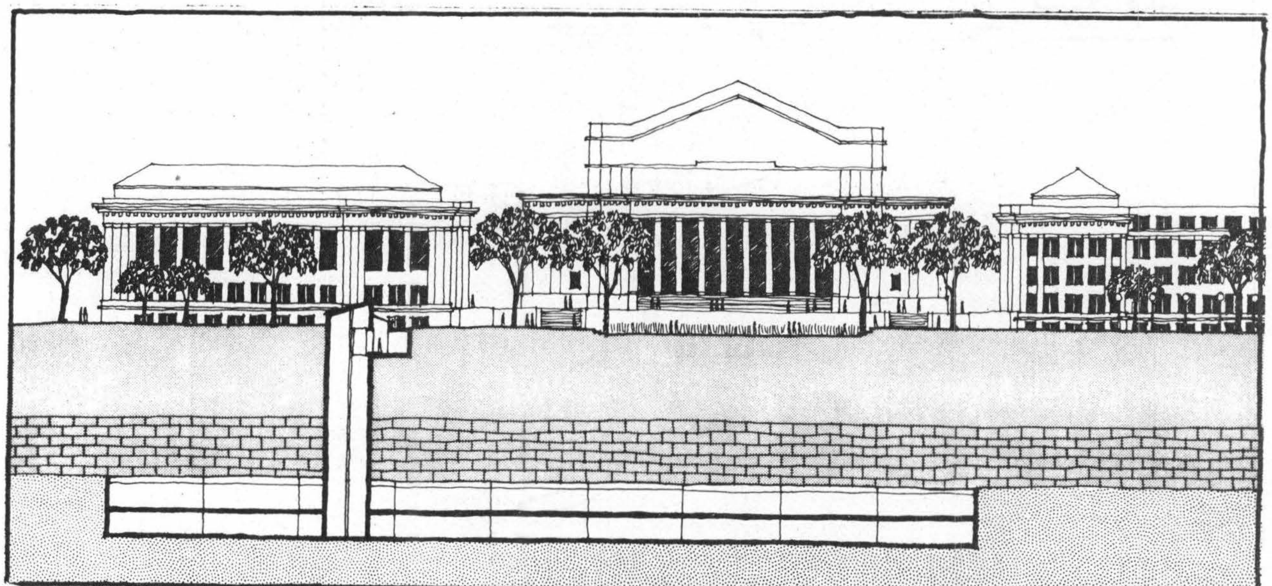
ITEM	QUANTITY	TYPE I	TYPE II
excavation	92,500 ft^2	$ 527,250	$ 527,250
walls	90,000	900,000	607,500
floor on grade	92,500	333,000	152,625
ceiling	92,500	485,625	485,625
internal structure	92,500	555,000	555,000
staircases	4	32,000	32,000
shaft	1/25'	330,100	330,100
SUB-TOTAL		$3,162,975	$2,690,100
COST/FT^2		$17.10	$14.54

remaining costs

access tunnel	600'	$ 195,000	$ 195,000
mech-elec		1,063,750	1,063,750
finishing		582,750	582,750
surface structure	1	50,000	50,000
SUB-TOTAL		$1,891,500	$ 1,891,500

totals

combined sub-totals		$5,054,475	$4,581,600
10% misc.		505,448	458,160
TOTAL		$5,559,923	$5,039,760
COST/FT^2		$30.05	$27.24



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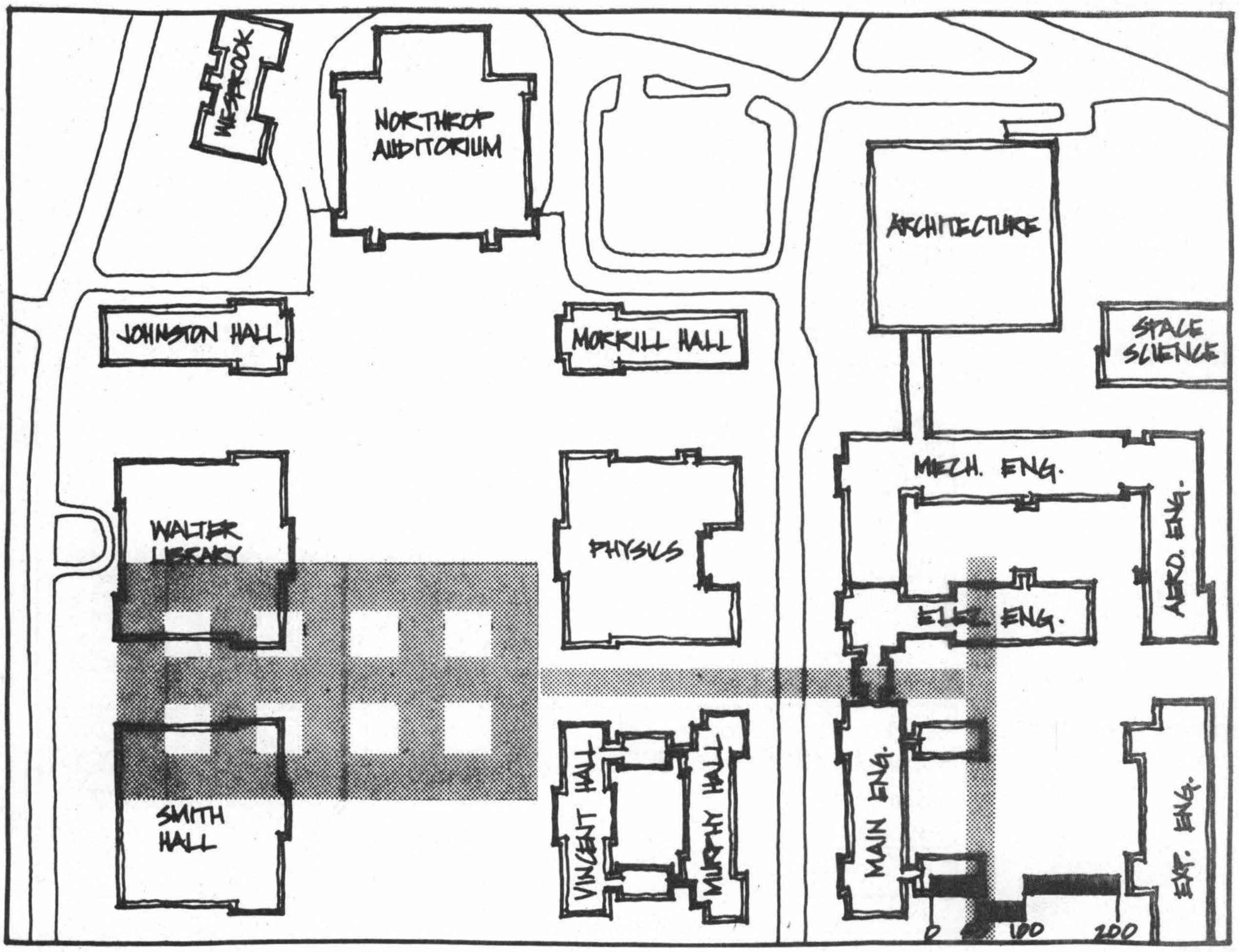
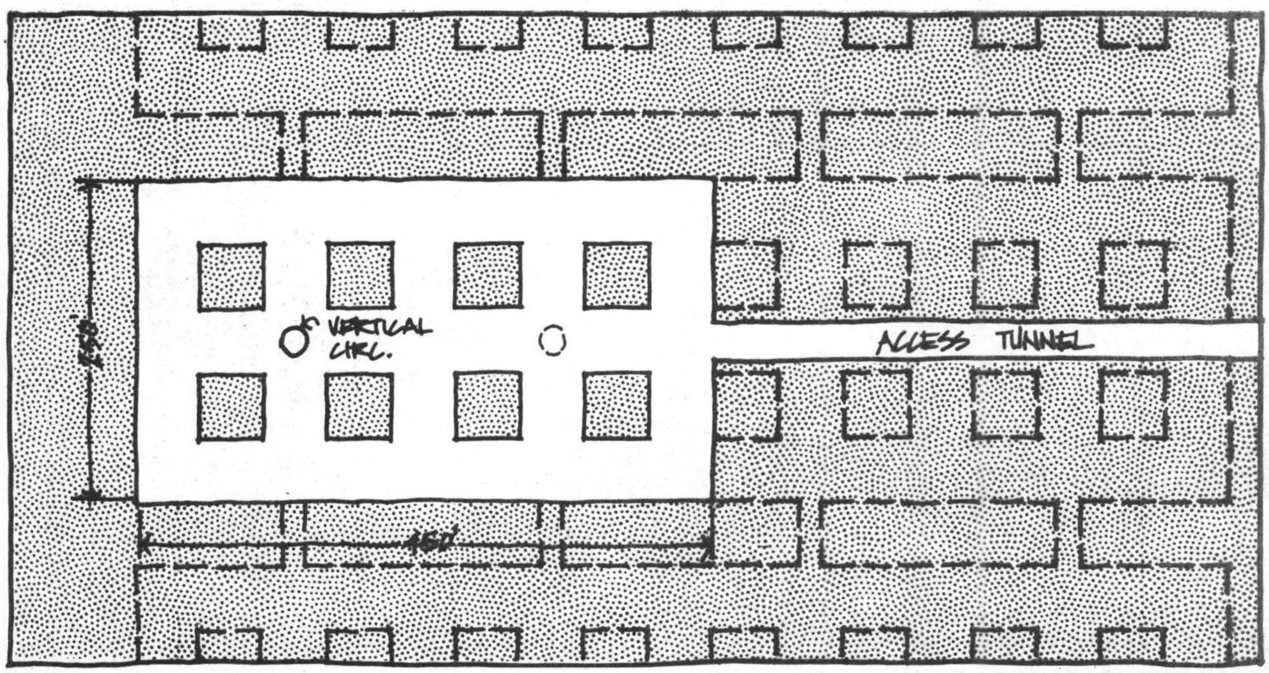


WESBROOK
NORTHROP AUDITORIUM
ARCHITECTURE
JOHNSTON HALL
MORRILL HALL
SPACE SCIENCE
MECH. ENG.
WALTER LIBRARY
PHYSICS
AERO. ENG.
ELEC. ENG.
SMITH HALL
VINCENT HALL
MURPHY HALL
MAIN ENG.
EXP. ENG.
0
100
200

site



VERTICAL CIRC.
ACCESS TUNNEL
150'

plan

b: parking garage

The parking layout illustrated here is approximately 381,600 ft^2 on two levels and contains space for 1008 cars. The plan layout is the rib system and close proximity to the bluffs is indicated. Although the cost of mined space compares well with many surface buildings, the cost of parking in mined space is somewhat higher. This is due to the obvious fact that surface parking structures are less expensive than almost any other type of building. It should be noted, however, that this project represents higher quality climate controlled space which can be easily converted to other uses in the future.

basic costs

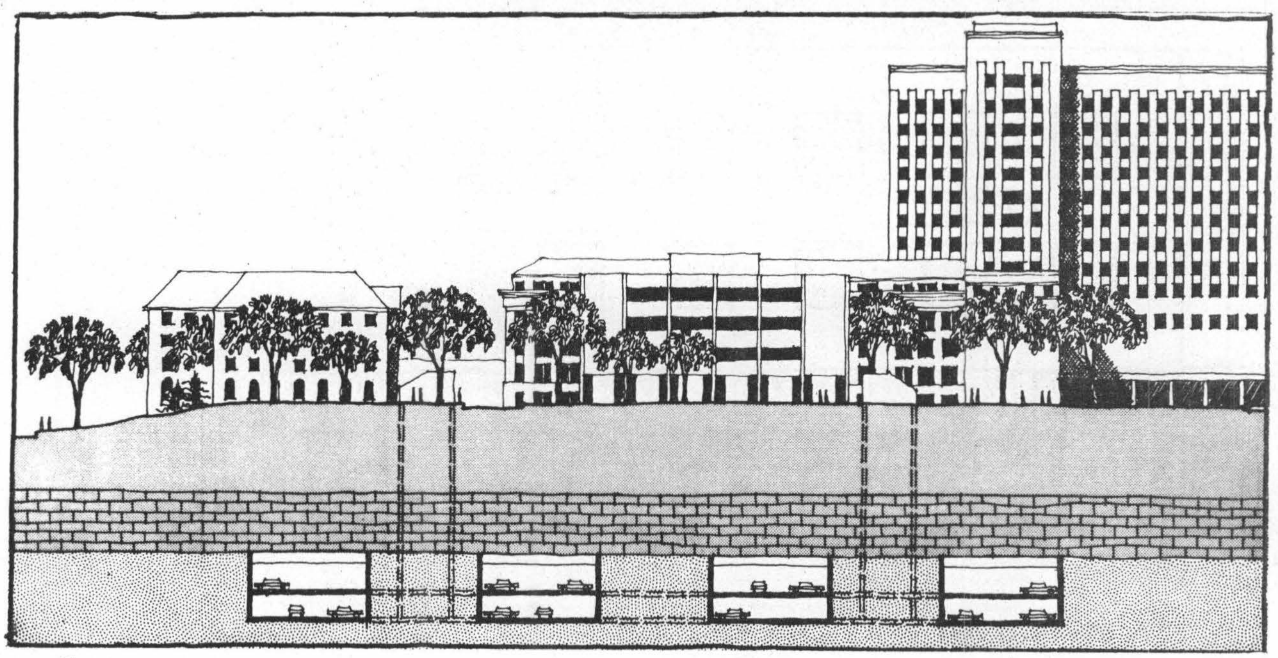
ITEM	QUANTITY	TYPE I	TYPE II	TYPE III
excavation	190,800 ft^3	$1,087,560	$1,087,560	$1,087,560
walls	210,600	2,106,000	1,421,550	421,200
floor	190,800	686,880	314,820	314,820
ceiling	190,800	1,001,700	1,001,700	1,001,700
internal structure	190,800	1,144,800	1,144,800	1,144,800
shafts	4/25' diam	1,412,800	1,412,000	1,412,000
SUB-TOTAL		$7,438,940	$6,382,430	$5,382,080
COST/FT^2		$19.49	$16.72	$14.10

remaining costs

ITEM	QUANTITY	TYPE I	TYPE II	TYPE III
surface structures	4	$150,000	$150,000	$150,000
portal, tunnel, ramps	780'	293,500	293,500	293,500
mech-elec		1,000,000	1,000,000	1,000,000
finishing		381,600	381,600	381,600
SUB-TOTAL		$1,825,100	$1,825,100	$1,825,100

totals

ITEM	QUANTITY	TYPE I	TYPE II	TYPE III
combined sub-totals		$9,264,040	$8,207,530	$7,207,180
10% misc.		926,404	820,753	720,718
TOTAL		$10,190,444	$9,028,283	$7,927,898
COST/FT^2		$26.70	$23.66	$20.16
COST/CAR		$10,110	$8957	$7865



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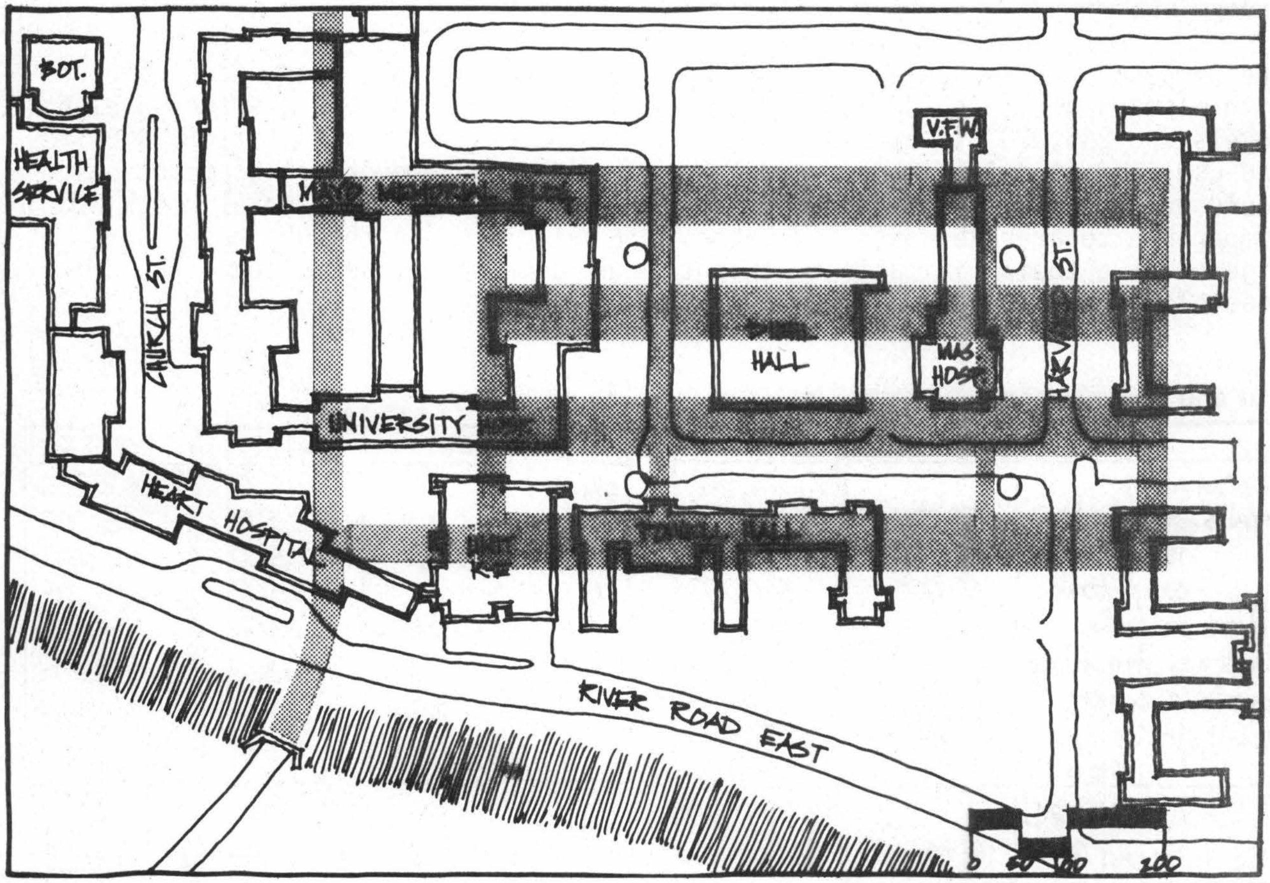
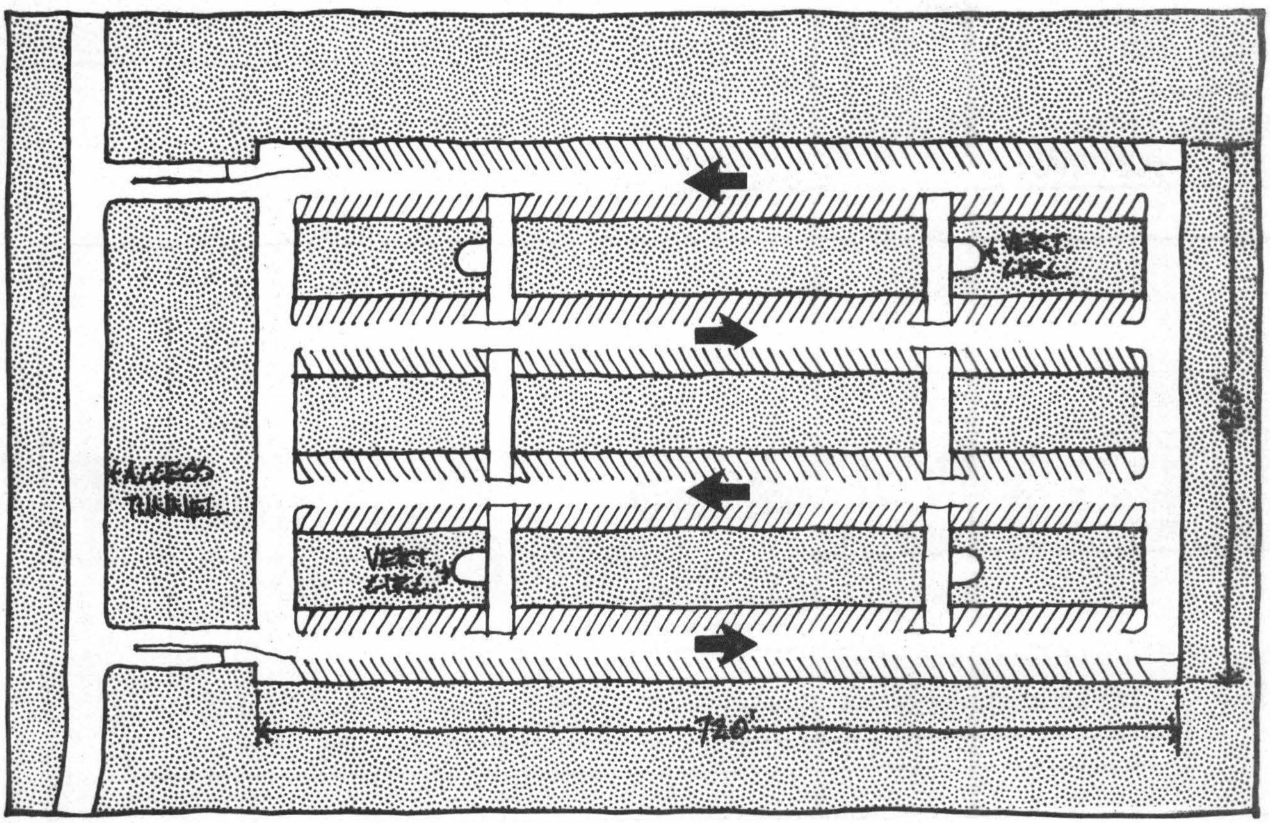

BOT.
HEALTH SERVICE
CHURCH ST.
UNIVERSITY HOSP.
HEART HOSPITAL
HALL
V.F.W.
MAS. HOSP.
RIVER ROAD EAST
0
50
100
200

site


VERT. CIRC.
ACCESS TUNNEL
VERT. CIRC.
720'

plan

c: research space

The purpose of this project is to illustrate deep cut and cover space combined with mined space. The design indicates 440,000 ft^2 of deep cut space on eight levels and 245,000 ft^2 of mined space on two levels for a total of 685,000 ft^2. The use indicated is research and laboratory space; however, other functions could be substituted with appropriate cost adjustments. The total costs are comparable to average costs for laboratory buildings. Although these cost figures have their limitations, this type of development seems to be economically feasible.

cut and cover space

ITEM	QUANTITY	TYPE I
excavation		$2,621,310
walls: overburden	50,000 ft²	437,500
limestone	30,000	300,000
sandstone	30,000	360,000
floor on grade	62,500	225,000
internal structure	440,000	2,970,000
surface cover	62,500	143,750
vert. circ.: elev.	6	833,400
stairs	6	244,800
SUB-TOTAL		$8,135,760
COST/FT²		$18.49

remaining costs

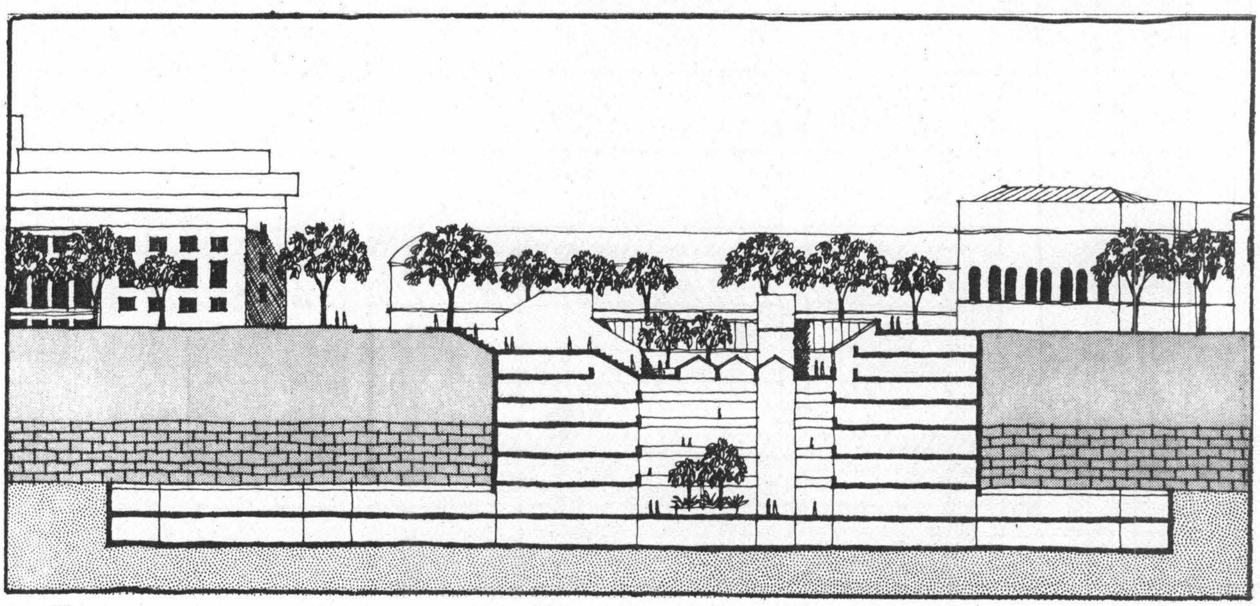
access tunnel	900'	$ 292,500
mech-elec.		16,241,350
finishing		4,904,600
surface/site	62,500 ft²	625,000
SUB-TOTAL		$22,063,450

mined space

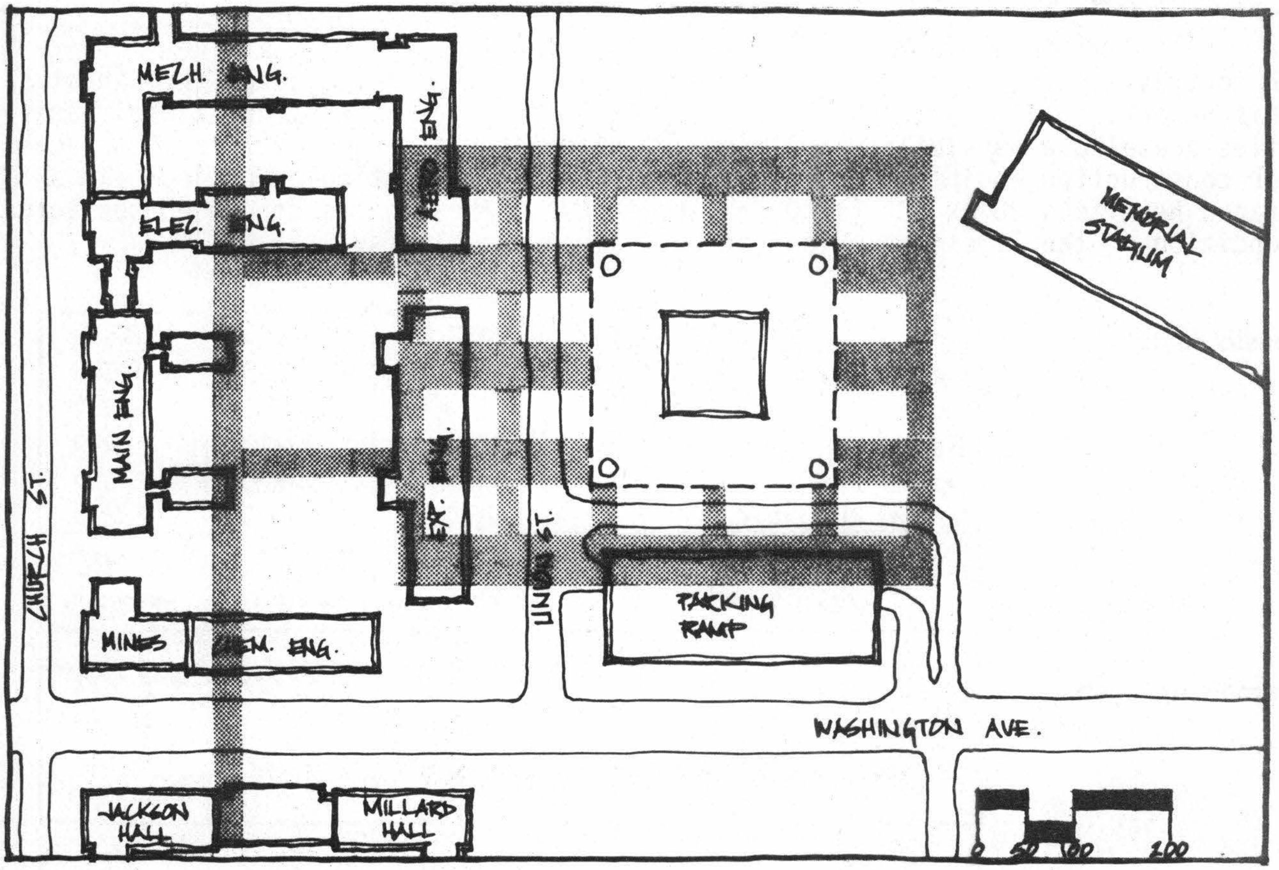
ITEM	QUANTITY	TYPE I
excavation	122,500 ft²	$ 698,250
walls	172,500	1,725,000
floor on grade	122,500	441,000
ceiling	122,500	643,125
internal structure	122,500	735,000
stairs	6	48,000
SUB-TOTAL		$4,290,375
COST/FT²		$17.51

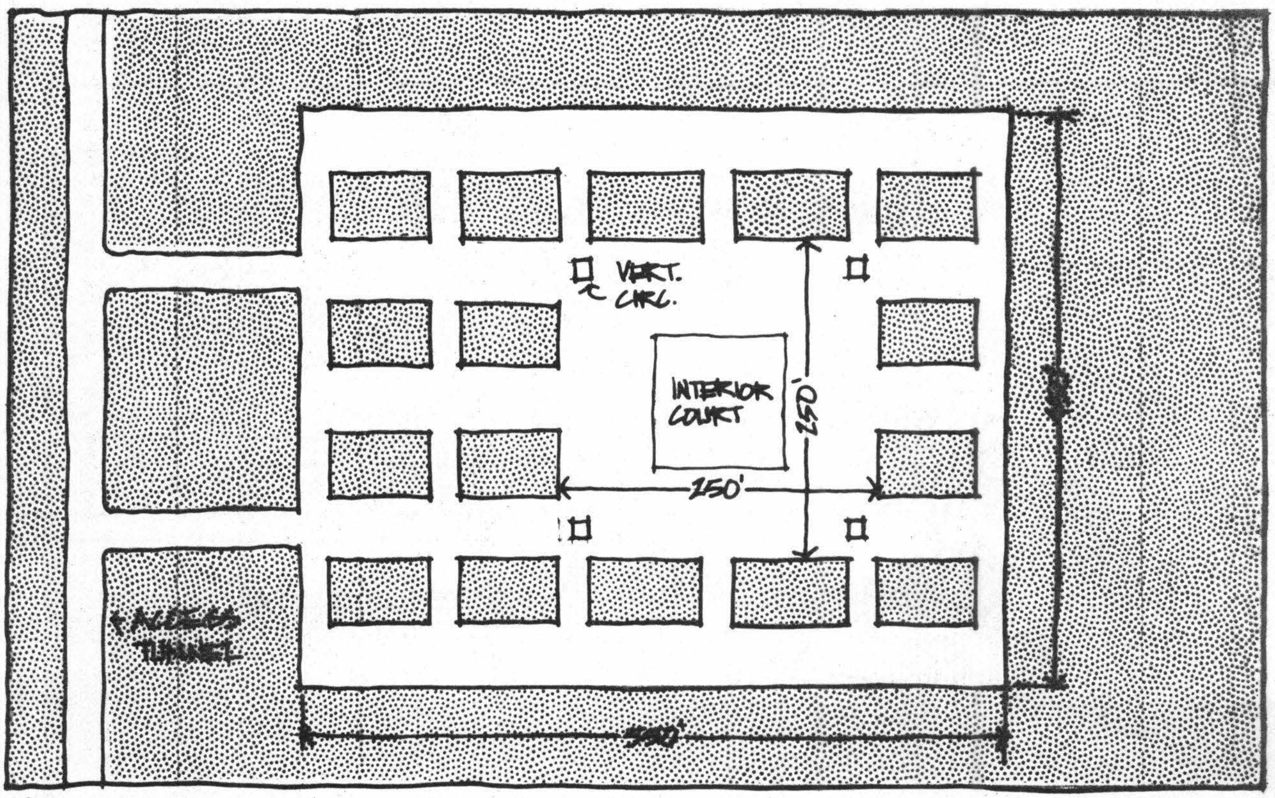
totals

combined sub-totals		$34,489,585
10% misc.		3,448,958
TOTAL		$37,938,543
COST/FT²		$55.38



section


MECH. ENG.
AERO ENG.
ELEC. ENG.
MAIN ENG.
EXP. ENG.
CHURCH ST.
UNION ST.
MINES
CHEM. ENG.
PARKING RAMP
MEMORIAL STADIUM
WASHINGTON AVE.
JACKSON HALL
MILLARD HALL
0 50 100 200
site


VERT. CIRC.
INTERIOR COURT
250'
250'
ACCESS TUNNEL
plan

d: boat storage

In contrast to the large scale development of mined space indicated throughout this report, smaller scale uses such as boat storage or other recreational facilities are also a possibility. Almost any site along the river bluffs with access for construction equipment would be appropriate. The particular project illustrated here is a 20' x 80' (1600 ft^2) boathouse. These costs depend on the actual condition of the limestone which can vary along the bluffs.

basic costs

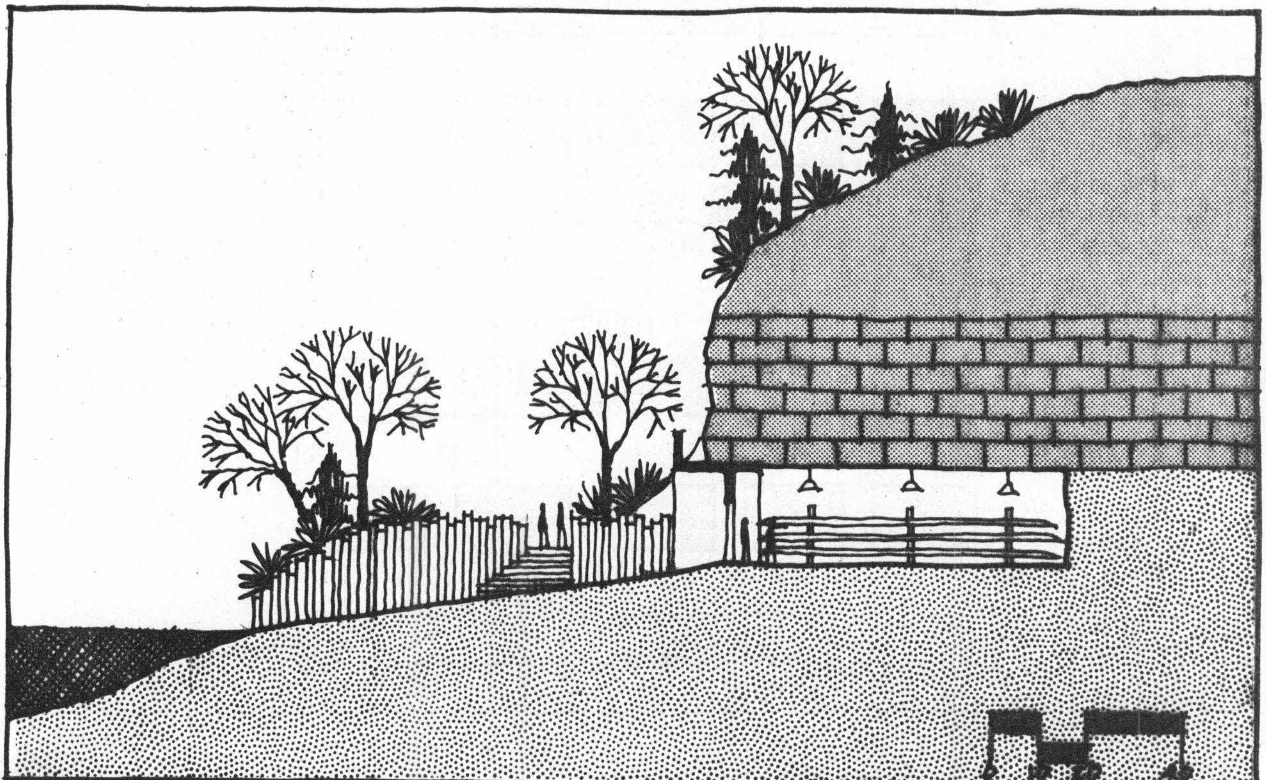
ITEM	QUANTITY	TYPE I	TYPE II	TYPE III
excavation	1600 ft^2	$5,760	$5,760	$5,760
walls	3060	30,600	20,655	6,120
floor on grade	1600	5,760	2,640	2,640
ceiling	1600	8,400	8,400	8,400
portal structure		8,000	8,000	8,000
SUB-TOTAL		$58,520	$45,455	$30,920
COST/FT^2		$36.58	$28.41	$19.33

remaining costs

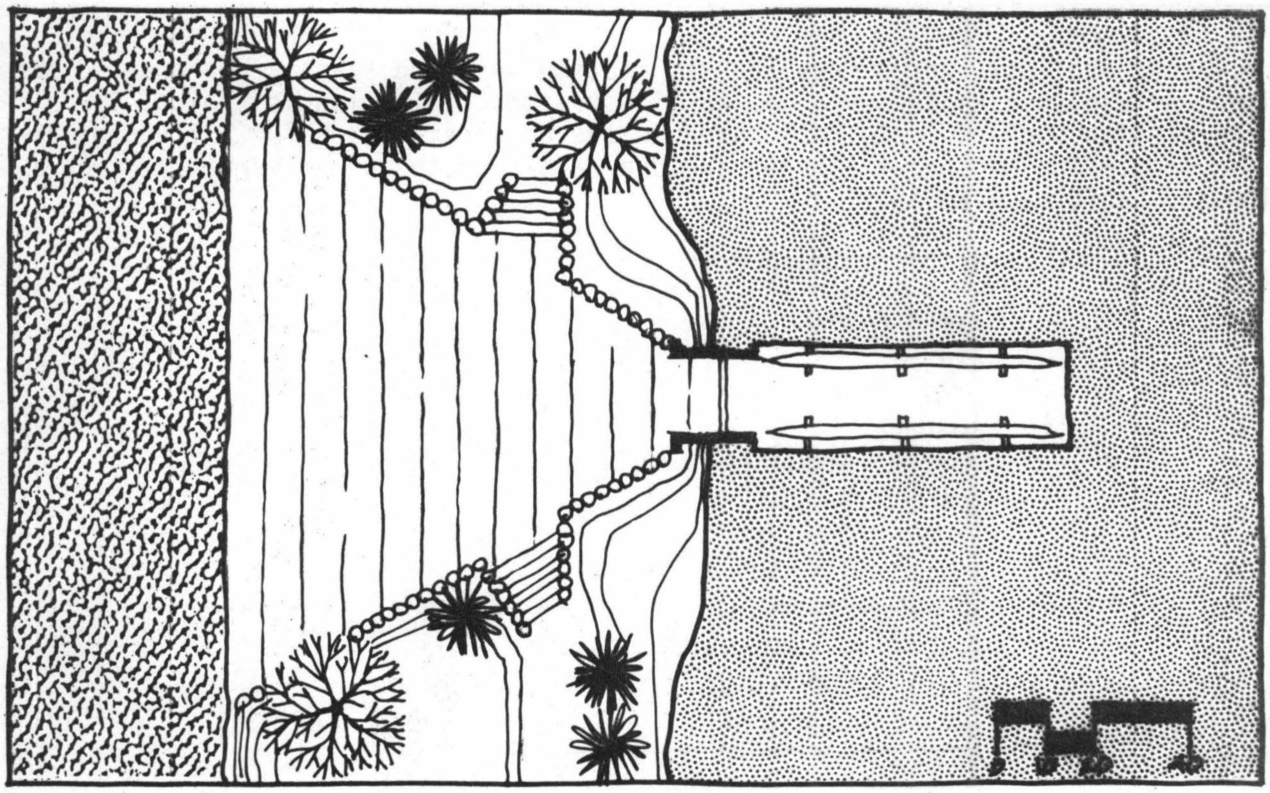
electrical		$2,000	$2,000	$2,000
sitework		8,000	8,000	8,000
misc.		5,000	5,000	5,000
SUB-TOTAL		$15,000	$15,000	$15,000

totals

TOTAL		$73,520	$60,455	$45,920
COST/FT^2		$45.95	$37.18	$28.10



section



plan

e: mass transit station

The layout and costs for a mass transit station in mined space are presented here since certain special features can be illustrated. This plan is typical for a major station such as would be located in the University area for a fixed guideway system. The high cost figures are due mainly to the great vertical circulation and shaft requirements.

basic costs

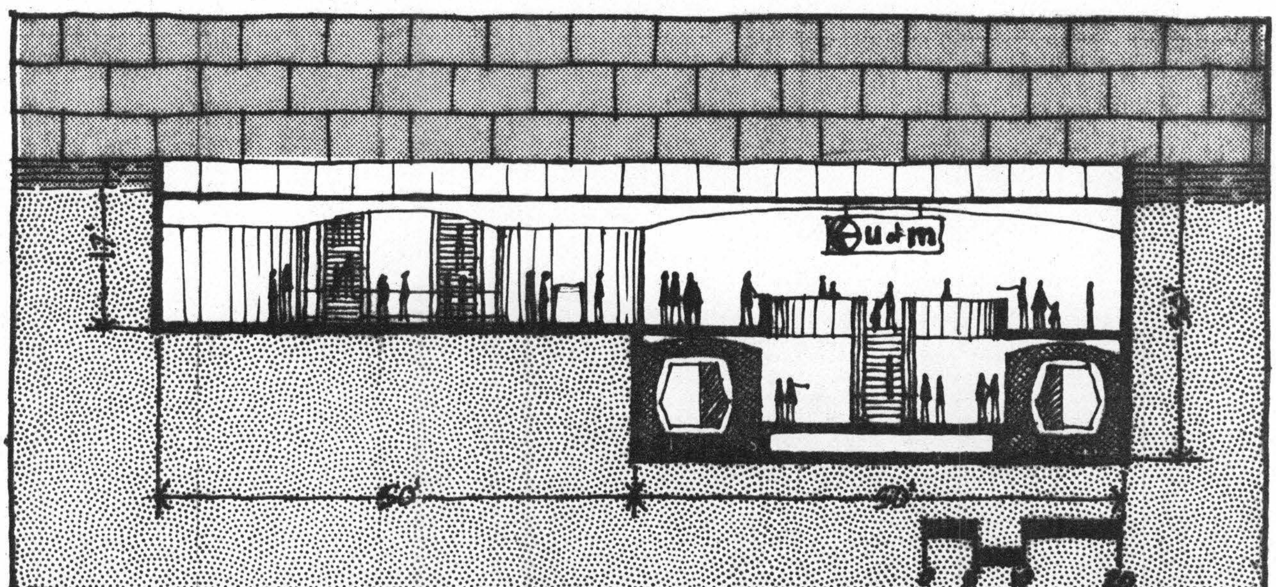
ITEM	QUANTITY	TYPE I
excavation		$ 130,130
walls	28,870 ft²	288,100
floor on grade	23,150	85,500
ceiling	23,150	124,690
internal structure	19,000	114,000
shafts: diagonal	1 (2 esc.)	1,022,280
20' el/stair	1	295,600
20' blast	2	310,000
conveyance: esc.	4	261,800
elev.	1	54,000
SUB-TOTAL		$2,686,700
COST/FT²		$89.57

remaining costs

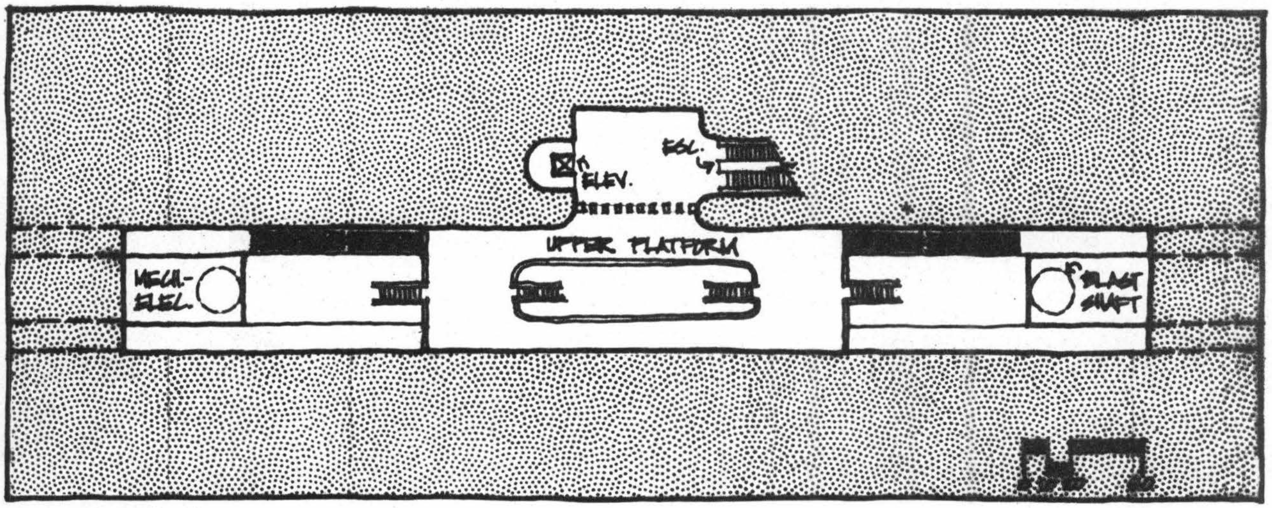
mech-elec.		$ 450,000
finishing		300,000
surface structures	2	100,000
SUB-TOTAL		$ 850,000

total

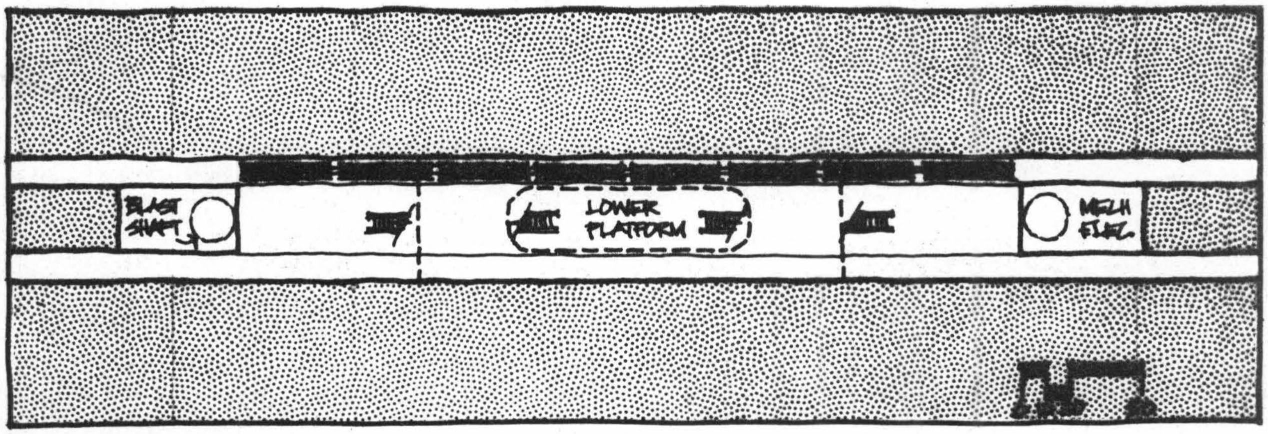
combined sub-totals		$3,536,700
10% misc.		353,670
TOTAL		$3,890,370
COST/FT²		$129.68



section



upper level plan



lower level plan